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Techniques for Green Radio Cellular Communications

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Abstract

This thesis proposes four novel techniques to solve the problem of growing energy consumption requirements in cellular communication networks. The first and second part of this work propose a novel energy efficient scheduling mechanism and two new bandwidth management techniques, while the third part provides an algorithm to actively manage the power state of base stations (BSs) so that energy consumption is minimized throughout the day while users suffer a minimal loss in achieved data rate performance within the system.

The proposed energy efficient score based scheduler (EESBS) is based on the already existing principle of score based resource allocation. Resource blocks (RBs) are given scores based on their energy efficiency for every user and then their allocation is decided based on a comparison between the scores of the different users on each RB. Two additional techniques are introduced that allow the scheduler to manage the user's bandwidth footprint or in other words the number of RBs allocated. The first one, bandwidth expansion mode (BEM), allows users to expand their bandwidth footprint while retaining their overall transmission data rate. This allows the system to save energy due to the fact that data rate scales linearly with bandwidth and only logarithmically with transmission power. The second technique, time compression mode (TCoM), is targeted at users whose energy consumption is dominated by signalling overhead transmissions. If the assumption is made that the overhead is proportional to the number of RBs allocated, then users who find themselves having low data rate demands can release some of their allocated RBs by using a higher order modulation on the remaining ones and thus reduce their overall energy expenditure. Moreover, a system that combines all of the aforementioned scheduling techniques is also discussed. Both theoretical and simulation results on the performance of the described systems are provided.

The energy efficient hardware state control (EESC) algorithm works by first collecting statistical information about the loading of each BS during the day that is due to the particular mobility patterns of users. It then uses that information to allow the BSs to turn off for parts of the day when the expected load is low and they can offload their current users to nearby cell sites. Simplified theoretical, along with complete system computer simulation, results are included.

All the algorithms presented are very straightforward to implement and are not computationally intensive. They provide significant energy consumption reductions at none to minimal cost in terms of experienced user data rate.

Declaration of originality

I hereby declare that the research recorded in this thesis and the thesis itself was composed and originated entirely by myself in the School of Engineering at The University of Edinburgh.

The only exception to the above is the MATLAB code used to simulate the wireless fading channel, which is partially based on a previous effort by Van Duc Nguyen and Birendra Ghimire.

Stefan I. Videv

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First and foremost, I would like to thank my parents not only for their love and care through the years but also for supporting me all through my education, and more importantly for instilling in me a curiosity and passion to learn through their own example. I dedicate this work to them.

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Acronyms and abbreviations

3G	third generation
4G	fourth generation
3GPP	3rd Generation Partnership Project
ABS	almost blank subframe
AWGN	additive white Gaussian noise
BEM	bandwidth expansion mode
BS	base station
BWS	bandwidth scheduling
CDF	cumulative distribution function
CDMA	code division multiple access
ECG	energy consumption gain
ECR	energy consumption rate
EESC	energy efficient hardware state control
EESBS	energy efficient score-based scheduler
FDMA	frequency division multiple access
FFT	fast fourier transform
FSPF	frequency selective proportional fair
GSM	Global System for Mobile Communications
HSPA+	evolved high speed packet access
ICT	information and communications technology
IEEE	Institute of Electrical and Electronics Engineers
LOS	line of sight
LTE	Long Term Evolution
MIB	master information block
MIMO	multiple input multiple output

MS	mobile station
NLOS	non-line of sight
OFDM	orthogonal frequency division multiplexing
OFDMA	orthogonal frequency division multiple access
PA	power amplifier
PF	proportional fair
PBCH	physical broadcast channel
PCFICH	physical control format indicator channel
PDC	Personal Digital Cellular
PDCCH	physical downlink control channel
PDSCH	physical downlink shared channel
PHICH	physical hybrid ARQ indicator channel
QAM	quadrature amplitude modulation
RB	resource block
RF	radio frequency
RRM	radio resource management
RSSI	receiver signal strength indicator
SB	score based
SCM	spatial channel model
SCME	spatial channel model extension
SINR	signal-to-noise-plus-interference ratio
SISO	single input single output
SNR	signal-to-noise ratio
TCoM	time compression mode
TDMA	time division multiple access
TS	time slot
UMi	urban micro cell
UMTS	Universal Mobile Telecommunications System
W-CDMA	Wideband CDMA

WiMAX	Worldwide Interoperability for Microwave Access
WINNER	Wireless World Initiative New Radio
ZDSC	zero delay-spread cluster

Nomenclature

C	channel capacity in bits/s
S	received signal power
I	interference power
E_{new}	total used energy in new system
E_{ref}	total used energy in reference system
J	Jain's fairness index
x_i	achieved throughput for user i
t	time slot index
$s^j(t)$	score for user j at time t in score based (SB) scheduler
$j(t)$	user assigned use of time slot (TS) t in SB scheduler
W	window size for rank computation in SB scheduler
$s_q^j(t)$	score for resource block (RB) q for user j at TS t in energy efficient score-based scheduler (EESBS)
$r_q^j(t)$	transmission rate for user j at TS t on RB q
$\mathbb{1}_{\{\cdot\}}$	indicator function which returns 1 if the condition in the curly brackets is true and 0 otherwise
X_l	independent identically distributed random variables on $\{0, 1\}$ with $\Pr(X_l = 0) = 1/2$
$E_q^j(t)$	energy metric evaluated for user j on RB q at TS t
M	is the total number of RBs
m_j	number of RBs allocated to user j
$f^j(m_j)$	EESBS scheduler penalty function based on m_j
P_q^j	radio frequency (RF) transmission power required on RB q for user j
Γ_q	SINR target for RB q
$\gamma_q^j(t-1)$	is the achieved signal-to-noise-plus-interference ratio (SINR) on RB q for user j at time $t-1$
ϵ	convergence threshold for power control algorithm
ϕ	overhead factor
P_{ref}	control channel transmission power

Γ_{ref}	control channel transmission SINR target
N_0	noise floor power spectrum density
$G_{\text{min}}(r)$	worst possible path gain for a distance r
G_{antenna}	antenna gain
I_{max}	maximum experienced interference at the cell edge on the downlink transmission direction
L	path loss in dB
d	distance
f_c	carrier frequency
h_{BS}	height of base station (BS)
h_{UT}	height of user terminal
p_n	power in the n^{th} zero delay-spread cluster (ZDSC)
τ_n	delay of the n^{th} ZDSC
θ_n	uniformly distributed random variable defined on $[0, 2\pi]$
K	number of different path components considered in fast fading model
f_{Dn}	maximum Doppler frequency
$P_{\text{BS,in}}$	required power drawn by the BS in Watts
$P_{\text{BS,0}}$	idle BS power consumption <i>i.e.</i> when no RF power is used
Δ_P	scaling parameter in BS hardware model
$P_{\text{BS,out}}$	required BS output RF power in Watts
$P_{\text{BS,out}}^{\text{max}}$	maximum permitted value of $P_{\text{BS,out}}$
$\lambda_q^j(t)$	PF metric used in the frequency selective proportional fair (FsPF) scheduler
$R^j(t)$	total rate achieved for user j at TS t in FsPF scheduler
$x_q^j(t)$	1 or 0 depending on whether user j can transmit on RB q at rate $r_q^j(t)$ in FsPF scheduler
α	bandwidth expansion factor for bandwidth expansion mode (BEM)
B_q	bandwidth of RB q
C_q	capacity of RB q
$E_{\text{used}}^{\text{RF}}$	total used RF energy for communication
P_{data}	total used RF power for data transmission
m	total number of RBs allocated in the system
I_q	interference received on RB q
I_q^j	interference received on RB q for user j

G_q^{kj}	path gain for RB q between transmitter k and receiver j
S_q	total received useful signal power for RB q
Γ_q^{BEM}	SINR target for RB q for the BEM system
A_q	constant representing channel conditions for RB q
P_q	minimum transmission power for required Γ_q
p_q^{BEM}	minimum transmission power for required Γ_q^{BEM}
D	delivered payload in bits
η	spectral efficiency in bits/s/Hz
B	total bandwidth used for transmission
β	bandwidth compression factor for time compression mode (TCoM)
R_{TCoM}	transmission rate for TCoM system
$R_{\text{benchmark}}$	transmission rate for benchmark system
Γ_q^{TCoM}	SINR target for RB q for the TCoM system
p_q^{TCoM}	minimum transmission power for Γ_q^{TCoM}
ζ	maximum allowed load increase
ψ	maximum allowed loss in user data rate
μ	initial probability for users to be at the home location
T	time of day in hours
$u_H(T)$	number of users at time T at home location
$u_W(T)$	number of users at time T at work location
$l_H(T)$	normalized load at time T at home location
$l_W(T)$	normalized load at time T at work location
u_{max}	maximum number of supported users at any one location
E_{FULL}	total energy used by FULL system
E_{EESC}	total energy used by energy efficient hardware state control (EESC) system
n_{BS}	number of BSs at each location

Chapter 1

Motivation

CELLULAR wireless communication systems have recently come under complex socio-economical pressure to significantly improve energy efficiency to meet profitability and newly imposed environmental constraints. Before the discussion on the possible ways to solve this challenge even begins, the context in which solutions are to be designed needs to be set. When it comes to increasing the energy efficiency of wireless communication systems, there are many sides to the system's operation to be considered. For example, energy costs should be analyzed from a holistic point of view – both manufacturing and operational costs need to be taken into account. This chapter aims to establish the context within which the enhancement of energy efficiency in wireless cellular systems is discussed, so that any solutions presented can be correctly evaluated.

The rest of this chapter is organized as follows. Section 1.1 lists the driving forces behind the need for improvement both in energy efficiency and throughput in wireless networks. It is followed by Section 1.2 which summarizes some of the main areas of research which promise to deliver the needed improvements in performance. The chapter concludes with Section 1.3 which presents the novel contributions and an outline of the remainder of this thesis.

1.1 Why is There a Need for Energy Efficient Wireless Communications

Ever since the first coining of the phrase "the Internet of things" by Kevin Ashton in a presentation for Procter & Gamble, there has been an expectation for the growth of required throughput in wireless networks [2]. Recently, the advent of the smart phone and the growing social aspects of the Internet have resulted in a significant increase in throughput in deployed cellular networks. These trends can be observed in the figures that present the information

and communications technology (ICT) sector developments in the last 10 years, Fig. 1.1, 1.2, 1.3, and 1.4 [3].

Fig. 1.1 presents the penetration and annual growth of ICT for the different sectors. The two major technologies which are experiencing an increase in user penetration are the mobile-cellular telephone subscriptions and the number of internet users. The number of fixed-telephone lines and fixed-broadband subscriptions appear to have saturated in recent years. A sector that is seeing growth recently is the active mobile-broadband subscriptions. This growth is very important as it is the main driver behind the research presented in this thesis. The penetration and annual growth of mobile-cellular subscriptions broken down between the developing and developed countries as well as a worldwide average can be found in Fig. 1.2. The growth in developing countries is significantly higher than that in already developed countries. This means that the problems expected in developing countries with regard to energy efficiency and system capacity would need to be addressed promptly so that the growth rate can be sustained. However, in terms of the mobile-broadband subscriptions penetration and annual growth presented in Fig. 1.3, the developed world is experiencing a steady growth in terms of absolute penetration, whereas in the developing world the amount of mobile-broadband subscriptions is just taking off in the past 2 – 3 years. Finally, Fig. 1.4 presents the annual growth and population penetration of internet users in the last decade for the developed and developing countries. In terms of absolute numbers, the number of internet users per 100 inhabitants in the developed world has gone from approximately 25 to almost 70, while at the same time in the developing countries the internet users per 100 people have gone up from just a few to a little over 20.

There are several trends of interest – the continual increase in the number of mobile-cellular subscriptions, the doubling of mobile-broadband subscriptions in the last 3 years, and the steady growth of Internet users across the globe. What this means for mobile phone carriers is that their networks will continue to get more and more congested with packet traffic demands. From an economic point of view, it is not desirable to solve this problem with today's technology. A prominent example of the problems associated with that are the recent coverage and service complaints that have overwhelmed AT&T in the United States of America [4,5]. What is also important to note is that these trends pertain not only to the developed world, but also to the developing countries. In developed countries, there is already established infrastructure that could potentially be upgraded to achieve better energy efficiency. However,

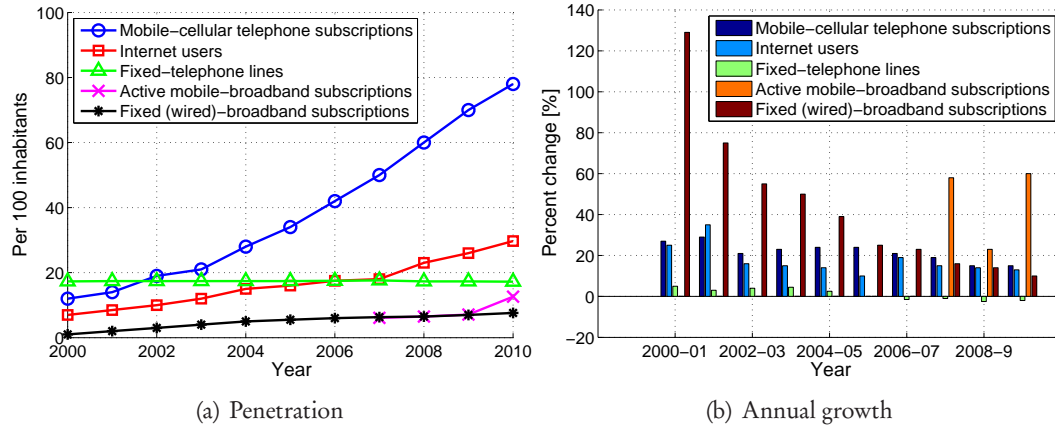


Figure 1.1: Global ICT developments, 2000 – 2010

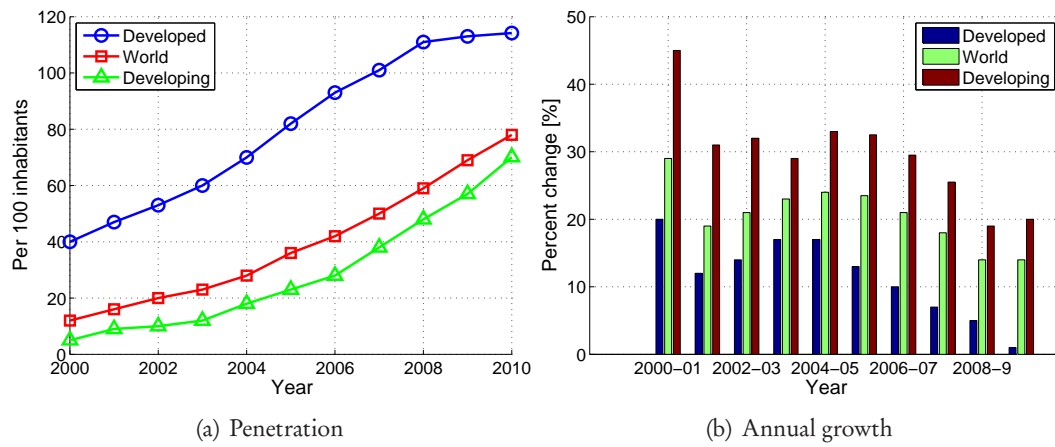


Figure 1.2: Mobile-cellular subscriptions, 2000 – 2010

in developing countries there is no established infrastructure – both in terms of wireless communications, as well as electrical grid. Hence, the problem of energy security emerges. The problem of energy security is not localized to only the developing countries, albeit it being much more serious there. The California electricity crisis in 2000 and 2001 is one prime example [6]. This is further exacerbated by the world's dependence on fossil fuels, and the recently established constraints on CO₂ emissions.

Moreover, the recent economic downturn means that service providers are not at liberty to make substantial investments in their networks or significantly increase the price of their services. All of these factors mean that a comprehensive solution that is able to decrease the energy consumption both in terms of operational and manufacturing costs while in the least maintaining, if not significantly improving, the already achieved system throughput is needed.

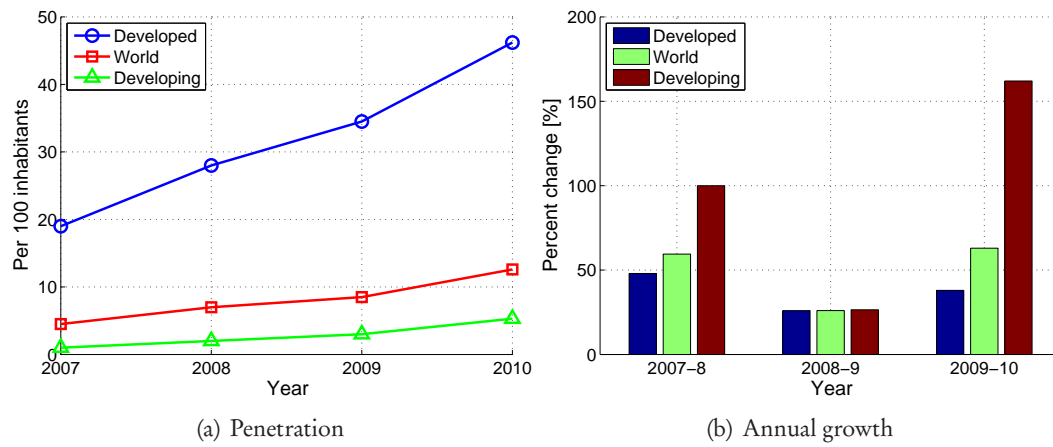


Figure 1.3: *Mobile-broadband subscriptions, 2007 – 2010*

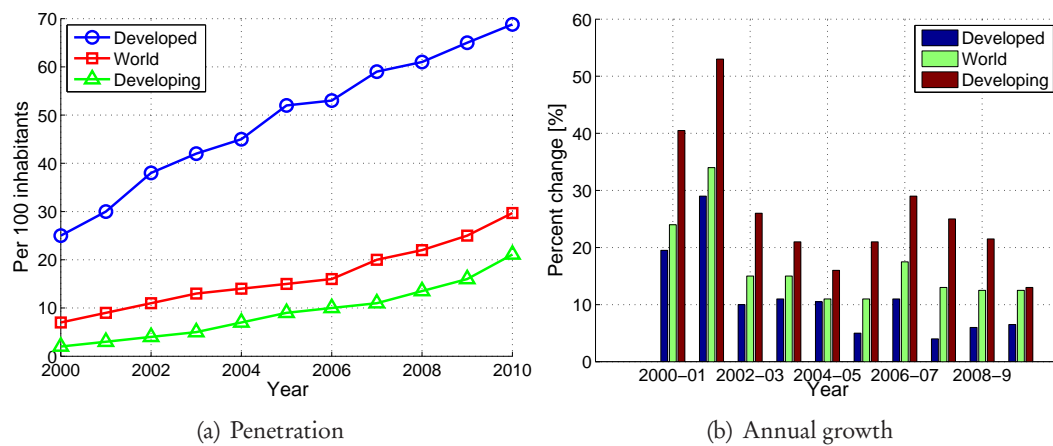


Figure 1.4: *Internet users, 2000 – 2010*

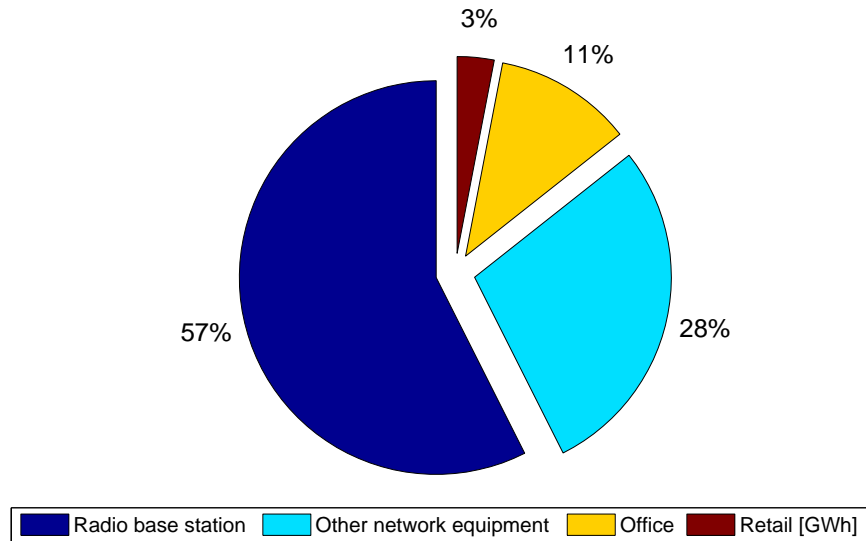


Figure 1.5: *Energy use breakdown for the Vodafone 3G network in 2007/08*

Another factor that necessitates the development of such techniques to reduce energy consumption are the corporate responsibility targets to reduce carbon emissions and environmental impacts of networks that some carriers have set themselves. For example, in the United Kingdom, Vodafone have set a target of reducing their CO₂ emissions by 50% by 2020 compared to their 2006/7 levels [7]. Another carrier that has pledged to a similar path is Orange – they target a reduction of 20% of greenhouse emissions per customer between 2006 and 2020 [8].

To really grasp what such a reduction in CO₂ emissions means, the way these emissions are generated needs to be understood. The energy consumption in a wireless network is dominated by the energy expended by the radio base stations (BSs) as demonstrated by Fig. 1.5 [7]. Energy consumption can be directly related to greenhouse gas emissions, which means that the energy consumption of BSs becomes a prime target for reduction if these aforementioned emission reduction targets are to be met. Another way to go about this would be to make sure that the energy that goes to power the operation of wireless networks is generated by green, renewable sources. Unfortunately, this is currently unsustainable due to the low contribution of such sources in the total energy generation worldwide.

Going back to the holistic perspective on energy consumption, Fig. 1.6 presents the energy in terms of CO₂ kgs that is required per user per year for the operation of a wireless network [9].

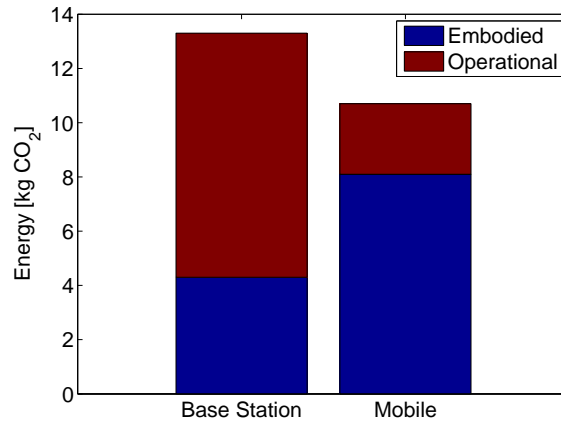


Figure 1.6: Breakdown of CO_2 emissions per subscriber per year

From an operational point of view, BSs are at a clear disadvantage currently with over 70% of their CO_2 expenditure going to operational energy. Hence, there is an opportunity for techniques that are able to reduce the required operational energy to make a significant impact. Reduction in embodied energy is outside of the scope of this work, but should still be kept in mind. Moreover, the techniques that are presented within this thesis reside on the software layer. It is assumed that they come with little to no cost in terms of added embodied energy.

A breakdown of energy consumption between the different BS components from the near past can be found in Fig. 1.7 [10]. The second smallest, and most important number is the percentage of transmit power. Only 3% of the power going into a BS is actually propagated through the antenna. This is important in two ways – it has already been identified as something to be improved, hence future BSs should have a better ratio of input to output power, and second, it creates an opportunity. The former is important because it needs to be kept in mind when techniques for energy efficiency are designed so they are compatible with this profile of BS energy consumption. The latter is also important because it is an opportunity for energy efficiency improvement techniques that require less BSs to be operational but at a higher operational radio frequency (RF) power load. This is indeed an opportunity because updated BSs will not be deployed for some time and increases in RF energy consumption are not significant when applied to a 3% base, if it leads to a number of BSs being completely turned off.

Another side of BS operation that can be exploited is load variation during the day. Fig. 1.8 presents the loading of a single third generation (3G) cell site in London as a function of time of day. The data is courtesy of Vodafone. It is important to note at this point, that this data

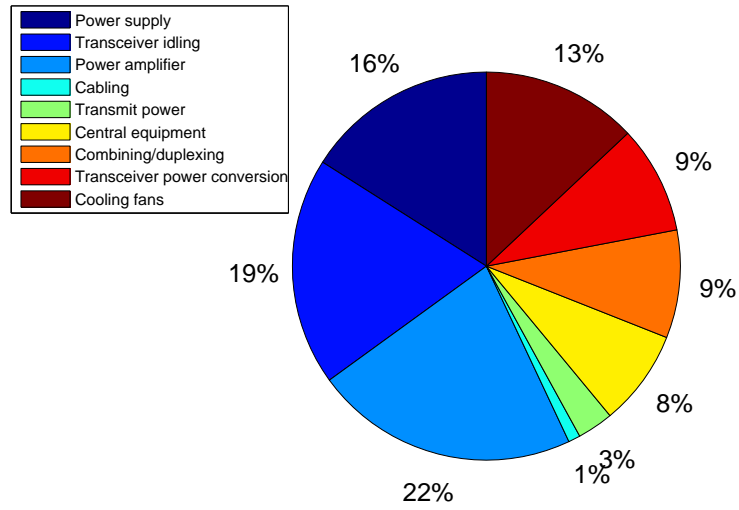


Figure 1.7: BS energy consumption breakdown

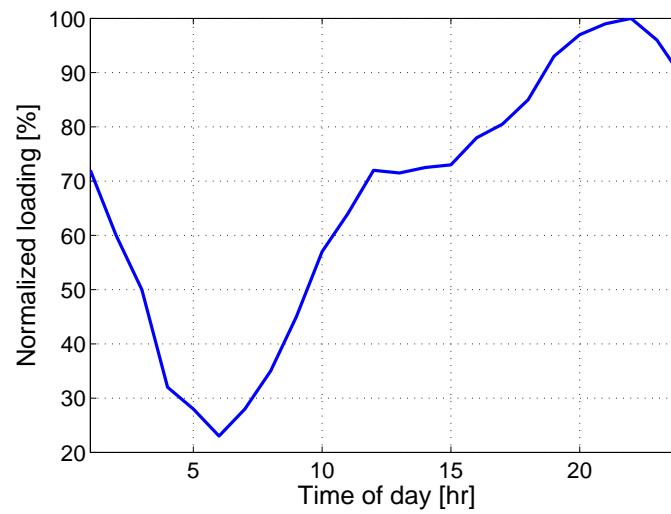


Figure 1.8: 3G network loading in London (averaged over 28 days) courtesy of Vodafone

Table 1.1: *Wireless Cellular Network Consumption*

Country	Network	Energy Consumption	% of Country Total Energy Consumption
USA	Verizon 2006	8.9TWh	0.24%
Japan	NTT 2001	6.6 TWh	0.7 %
Italy	Telecom Italia 2005	2 TWh	1 %
France	France Telecom-Orange 2006	2 TWh	0.4 %
Spain	Telefonica 2006	1.42 TWh	0.6 %

is not representative for the entire network. There will be significant variation between the the loading characteristics of different cells in the network. There are significant periods of low loading. In these periods there are a lot of frequency and time resources free in the BS that can be utilized to reduce the energy consumption, or alternatively the users connected can be handed over to another nearby BS, allowing a number of the cell sites to be turned off. This presents tremendous opportunity for reductions in used energy compared to currently deployed BSs which are static with regard to the way they operate during the day.

Having established that there are indeed opportunities to decrease the total energy consumption of wireless cellular networks, the next question emerges – is the total energy consumption of these networks significant? Table 1.1 presents total energy consumption data for several different networks as percentage of the total energy consumption of the countries they reside in [11]. As evidenced by the data, even a single wireless cellular networks do indeed constitute a significant portion of the total energy used by a country. If the data were extrapolated for the number of carriers in each country, as well as the growth that has inevitably occurred since the data was collected, it becomes clear that cellular networks are indeed a major consumer of energy.

The combination of technical, economical, and ecological pressure means that progress in energy efficiency is going to be critical for the continued success of cellular wireless communications in the future. Radio BSs are identified as one of the main contributing factors towards the high energy consumption, and a promising potential element of the complete system to be improved.

1.2 What are the Proposed Ways in which Energy Efficiency can be Achieved

In general, there are two approaches that can be taken to reduce the energy consumption of wireless cellular networks. First, there is the architecture approach, which relies either on the re-deployment of already existing hardware, or the introduction of new types of equipment, for example femto cells [12]. The second approach is where techniques are developed that rely on changing the operation of the existing infrastructure towards better energy efficiency.

The currently deployed infrastructure of wireless cellular networks is largely homogeneous. Research in the sector of architecture has suggested the use of femto and pico cells along with relays and the already deployed BSs to achieve better coverage and throughput along with decreasing the operational energy needed due to the lower distances that signals have to travel [13, 14]. This solution requires careful consideration of each deployment in order to strike a good balance between embodied energy and cost, and their operational counterparts. In relation to that, researchers have looked into strategies for optimum deployment of hardware to reduce the energy consumption while maintaining the quality of service [15–21]. Other concepts such as spectrum balancing, optimum cell size, and single input single output (SISO) versus multiple input multiple output (MIMO) are also being investigated [22–28]. Handing off users to other networks based on technologies like WiFi to both ease the operation of the network in terms of throughput, but also to improve the energy efficiency by cutting down the distance between receiver and transmitter is also an option [29–31].

The idea behind most of the techniques targeted at energy reduction is to move away from a pre-designed system that is calibrated for a particular usage scenario to a more dynamic one that is able to respond to the current conditions at the time. The three main avenues of research are scheduling, interference mitigation, and sleep modes. Scheduling is concerned with the best way to allocate resources to users so that the system behaves optimally both from a quality of service as well as energy efficiency point of view. Interference avoidance and mitigation techniques focus on reducing the interference within the system, which in turn promotes higher energy efficiency and/or higher data rates. Sleep modes are designed to follow the load in the system by turning off parts of the deployed hardware in order to save energy. Unfortunately, the latter often results in some detriment to the quality of service and data rate delivered to the users. Recently, a new concept has emerged – mechanical relaying [32–34].

Close-by user terminals traveling on trajectories expected to encounter better channel conditions are used to relay data from users which are either stationary or not expected to improve their connections to the deployed architecture hardware in the near term.

Another avenue, not discussed in detail within this thesis, is the improvement of hardware. Currently, the state of the art deployed BS efficiency in terms of delivering RF transmission power is between 5–15%. There is a significant drive in industry to improve that by achieving substantial improvements in the efficiency of power amplifiers and reducing the energy needed for cooling [11, 35–42]. Improvements in hardware are important, and likely to generate substantial energy savings. What is important within this work is to be able to model the behaviour of current and future BSs accurately, so that any proposed techniques are properly evaluated and later on integrated in the overall system.

This thesis presents work within the realm of energy consumption reduction techniques, as well as an algorithm similar in concept to the idea of sleep modes. There are three scheduling techniques presented and subjected to both theoretical and empirical analysis of performance. Alongside them, a hardware power state control algorithm is introduced that is able to improve energy efficiency. All proposed techniques have minimal undesirable side effects to the users' perceived quality of service.

1.3 Thesis Outline and Contributions

The rest of this thesis is structured as follows: Chapter 2 provides essential background information as well as summarizes a part of the current state of the art on the topic of reducing energy consumption through advancements in architecture and techniques.

Chapter 3 introduces the first contribution, energy efficient score-based scheduler (EESBS), a scheduler targeted at improving energy efficiency and fairness with no detriment to, and in cases improvement of, data rate. EESBS is based on the known score based scheduling principle. The novelty in EESBS compared to a regular score based scheduler stems from the fact that the proposed scheduler is targeted at simultaneously achieving energy efficiency, fairness, and data rate improvements over currently used schedulers. The additional functionality compared to a regular score based scheduler is achieved by the choice of the score calculation metric and penalty functions, the way scores are calculated across users and resource blocks (RBs) and the conflict resolution process used when two resource allocations have the same scores.

This is followed by Chapter 4 which discusses two bandwidth scheduling mechanisms, bandwidth expansion mode (BEM) and time compression mode (TCoM), which are meant to be used together with EESBS. BEM exploits any available frequency resources in the system to allow users to switch to more energy efficient modulation schemes, and hence reduce energy consumption and improve the robustness of transmissions. TCoM is aimed at reducing the energy consumption of users who experience good channel conditions by reducing the number of frequency channels allocated to them in order to reduce the energy required for overhead transmissions, and hence reduce the total energy expended for communication.

The last contribution is the energy efficient hardware state control (EESC) algorithm, which is outlined in Chapter 5. The algorithm exploits the users' stable movement patterns during the day to predict the loading at BS sites and preemptively allow them to turn on or off to save energy, but at the same time be able to retain the required quality of service. Not only are significant energy savings achieved by doing so, but also any erratic change of power state of the infrastructure is avoided.

This work concludes with Chapter 6. All papers and a patent that constitute the published work from this thesis are available in the appendix.

Chapter 2

Relevant Background

THIS chapter aims to first briefly introduce the history of wireless communications as part of setting the context within which the challenge of improving energy efficiency lies. This is followed by background information on wireless cellular systems and the ways to evaluate their performance which is essential to the understanding of this work. Finally, a brief overview of current state of the art techniques that show promise to drive cellular networks towards being more energy efficient is presented.

2.1 Wireless Communications Through The Years

One could speculate that wireless communications date back as far as the use of drums for communication, or even the signal torches used in ancient Greece. However, wireless communication in the sense of using electromagnetic waves to carry information through the air did not start to emerge until 1878 when David Hughes noticed his induction balance caused noise in the receiver of his homemade telephone. Unfortunately, his findings were dismissed as merely a manifestation of the known principle of induction. It was in 1887, when Heinrich Hertz was able to empirically prove the existence of electromagnetic waves that kick started scientists into developing apparatus that are capable of communicating wirelessly. Probably the best known invention in the field of wireless communications is the wireless telegraph which was demonstrated to the English telegraph office by Guglielmo Marconi in 1896.

The following century brought significant advancements. In 1919, the first clear transmission of human speech over wireless was made. By the end of the 1930s, mobile radio transmitters for the use of emergency services were already developed and deployed in the field. In 1947, AT & T commercialized its Mobile Telephone Service. It was the first of its kind with only three radio channels available for simultaneous use and approximately 5000 customers. Thirty years later, the first analog cellular system, Advanced Mobile Phone System, was deployed in

North America. It was not encrypted making it easily susceptible to eavesdropping by using devices known as scanners. It was based on a frequency division multiple access (FDMA) scheme which required a large amount of bandwidth. In the 1990s, the second generation of mobile phone systems emerged. Two systems competed for the global market – Global System for Mobile Communications (GSM) and code division multiple access (CDMA). GSM was first introduced in Finland, as it was developed in Europe. CDMA, also known as IS-95 and cdmaOne, was the competing standard developed by the company Qualcomm. A different system, Personal Digital Cellular (PDC), was developed and used exclusively in Japan. It is also based on time division multiple access (TDMA) similar to GSM. It did not take long until the first Internet service named i-mode on mobile phones was introduced by network provider NTT DoCoMo in Japan in 1999.

Demand for more data oriented services became clear during the operation of the second generation mobile phone systems. This prompted industry to start developing the next, third, generation. The most significant difference between the second and third generation technology was the switch from circuit to packet switching for data transmissions. Again, two standards emerged as competitors – Universal Mobile Telecommunications System (UMTS) and CDMA2000. The first one is based on the Wideband CDMA (W-CDMA) radio interface, and is primarily used in Europe, Japan and China. It is capable of delivering up to 28 Mbit/s on the downlink and up to 22 Mbit/s on the uplink. The latter system is based on the IS-95 second generation standard, and it is popular in North America and South Korea. In its latest revision it is capable of delivering up to 14.7 Mbit/s on the downlink channel direction. However, these achieved speeds are deemed insufficient. The latest UMTS enhancement, evolved high speed packet access (HSPA+), provides up to 84 Mbit/s on the downstream with Release 9 of the 3rd Generation Partnership Project (3GPP) standards.

In recent time, it has become clear that third generation (3G) networks would eventually be incapable of supporting the ever growing demand for more traffic. Hence, industry has started working on data optimized technologies that are targeted at improving the throughput up to 10 fold. The first two technologies that comply to the fourth generation (4G) specifications to be commercially deployed are Worldwide Interoperability for Microwave Access (WiMAX) and Long Term Evolution (LTE). One of the main advantages of 4G over 3G is the elimination of circuit switching, which means that voice calls are treated in the same way as any other media, by being transmitted as packets over the network.

This thesis focuses on developing techniques targeted at improving the energy efficiency performance of LTE type networks while making sure the achieved data rate is retained. The next section presents background information that facilitates the understanding of the concepts presented further on in this work.

2.2 Background Information

2.2.1 Energy Efficient Metrics

To be able to compare the energy efficiency of two systems, there needs to be a measurable quantity that can be compared between the two. Moreover, this quantity should be independent of the type of system it is applied to so it does not introduce subjective bias. Two energy efficiency metrics are used within this thesis – energy consumption gain (ECG) and energy consumption rate (ECR) [43]. These metrics are the result of research performed within Core 5 of the Mobile Virtual Center of Excellence research initiative, and are not part of the contributions of this thesis. ECG is a relative measure of energy efficiency which directly compares the performance of two systems. It is calculated as:

$$\text{ECG} = \frac{E_{\text{ref}}}{E_{\text{new}}}, \quad (2.1)$$

where E_{ref} is usually the energy required for operation by a reference, benchmark, system, and E_{new} is the energy required by a proposed, new, system that is being evaluated. Values of ECG greater than 1 signify that the new system performs better than the benchmark, and conversely values lower than 1 mean that the benchmark is more energy efficient.

ECR is a measure of how efficiently data is delivered within the system. For example, for the proposed system it would be calculated as:

$$\text{ECR} = \frac{E_{\text{new}}}{D}, \quad (2.2)$$

where D is the delivered payload by the system in bits. Since ECR is measured in Joules per bit, the lower the value, the better the efficiency of the system.

ECG and ECR look at energy efficiency from two different viewpoints, and when used together can provide insight into the energy consumption of communication systems. However,

they give little consideration to the achieved overall quality of service or fairness in the system. This is why it is necessary to analyze them in conjunction with a set of metrics designed to represent quality of service.

2.2.2 Need for Additional Metrics of Quality of Service

Reducing the energy consumption of a system is meaningless when the user throughput is not maintained. Hence, considering ECG and ECR alone is not sufficient. In order to avoid undesired system behaviour, additional system parameters need to be considered. Within this work, as metrics of quality of service the cumulative distribution function (CDF) of user data rate is considered as well as average user data rate as a function of distance from the base station (BS).

The CDF of user data rate provides information on what percentage of the users find themselves in outage, as well as the user data rate as a function of percentile. The latter is a great tool for determining the minimum quality of service that users enjoy in the system. It is also helpful for gauging the fairness in the system. The slope and general features of the CDF curve hold valuable information regarding the fairness. On the other hand, user data rate as a function of distance from the BS gives information on coverage characteristics of the system. It also provides a measure of fairness in the system with regard to user distance from the BS.

A common measure of fairness used in communications is Jain's fairness index [44]. It is calculated as:

$$\mathcal{J}(x_1, x_2, \dots, x_n) = \frac{(\sum_{i=1}^n x_i)^2}{n \sum_{i=1}^n x_i^2}, \quad (2.3)$$

where there are n users and x_i is the throughput for user i . The result ranges between $\frac{1}{n}$ and 1, where 1 is the best case where users receive the same throughput.

2.2.3 Orthogonal Frequency Division Multiple Access

4G systems are expected to be based on the orthogonal frequency division multiple access (OFDMA) scheme. It is hence important to have good understanding of its operation as well as make sure any research work is compatible with it. OFDMA is the multiple access extension of the digital modulation scheme orthogonal frequency division multiplexing (OFDM). A box diagram of a OFDM transmitter can be found in Fig. 2.1 and the corresponding diagram

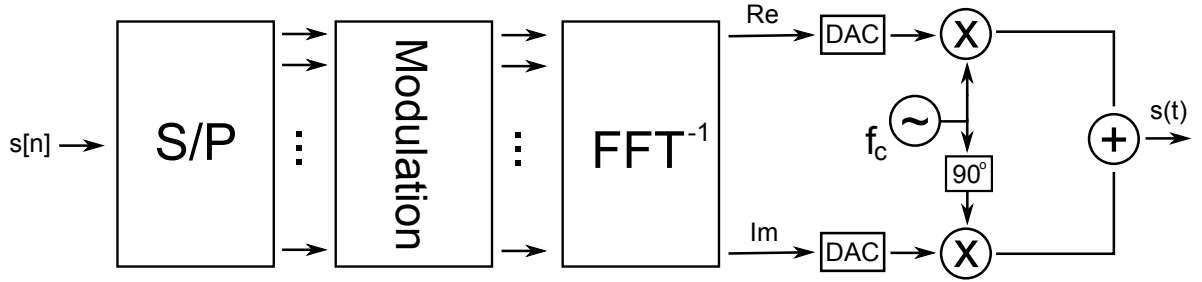


Figure 2.1: OFDM transmitter

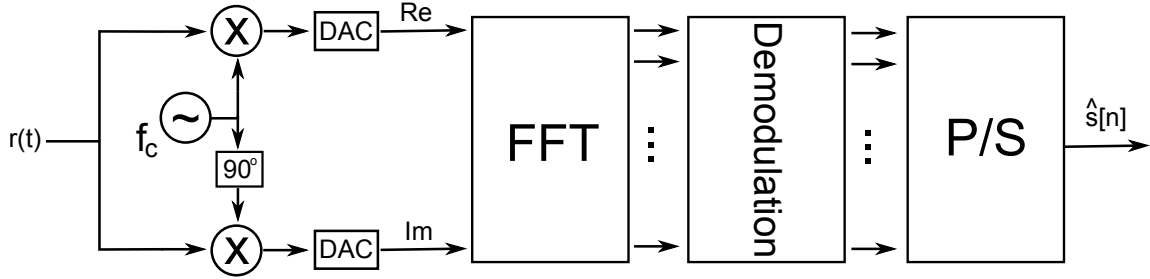


Figure 2.2: OFDM receiver

of a receiver is presented in Fig. 2.2 [45]. In OFDMA, the operational bandwidth is divided into a number of sub bands called frequency chunks. Each chunk, or resource block (RB), can be assigned to a user, by assigning different frequency chunks to different users, simultaneous communication without interference is achieved.

Compared to CDMA, OFDMA has both advantages and disadvantages. Some of those are included below.

OFDMA is better at handling multipath, and does not suffer from the well known effect of cell breathing present in CDMA [46–48]. Having many frequency RBs to allocate to users means that there is an additional degree of freedom when trying to reduce interference. It is possible to use different RB permutations between users in nearby cells. OFDMA is also able to provide frequency diversity by spreading a particular user's assigned RBs over the complete bandwidth. Lastly, the granularity of the bandwidth in OFDMA allows the system to control transmission power on each chunk, which can be beneficial in reducing interference as well as improving energy efficiency.

Unfortunately, it is not only good news with the introduction of OFDMA. Partitioning the frequency and assigning different parts of it to different users means that the system becomes

more sensitive to frequency offsets and phase noise [49–51]. If the complete bandwidth is to be reused in every single cell, co-channel interference mitigation becomes more complex than in CDMA since it requires smart dynamic channel allocation. Also, to make the RB allocation efficient and robust, there is a need for a more complex channel feedback information than in CDMA, as well as having adaptive resource allocation in general. The added complexity also results in higher energy consumption by the electronics in the BS unless in the future the system scheduler is given the capability to turn some of those off when there are no packets scheduled for transmission.

2.2.4 Long Term Evolution

LTE is one of the proposed 4G systems. It is based on OFDMA. It supports several transmission modes on each RB including both single input single output (SISO) and multiple input multiple output (MIMO). The system is designed with the goal of achieving a frequency reuse of 1 in a cellular deployment.

Power control is one topic that is important when it comes to energy efficiency. LTE has support for two types of power control on the uplink – open loop and closed loop [45]. The open loop power control establishes a transmission power that is corrected for the slow fading channel, and the closed loop power control is used to make either accumulated or absolute power corrections. The process is facilitated via feedback of information over control channels. In the downlink, dynamic power control is provided [45]. However, there is no direct feedback on the power control commands, power allocation is based on the downlink channel quality feedback from the mobile station (MS).

As any other cellular system LTE also has a certain frame structure and control channel architecture that facilitates communication. Both these are discussed in more detail in the next chapter.

2.2.5 Assessment of Energy Efficiency of the Transmission Chain in Wireless Communications

Currently, 3G base stations have an overall efficiency of between 5% and 15%. This is due to the varying efficiency of different elements along the transmission chain. A simple box diagram of a BS is presented in Fig. 2.3. For example, the climate control is only approximately

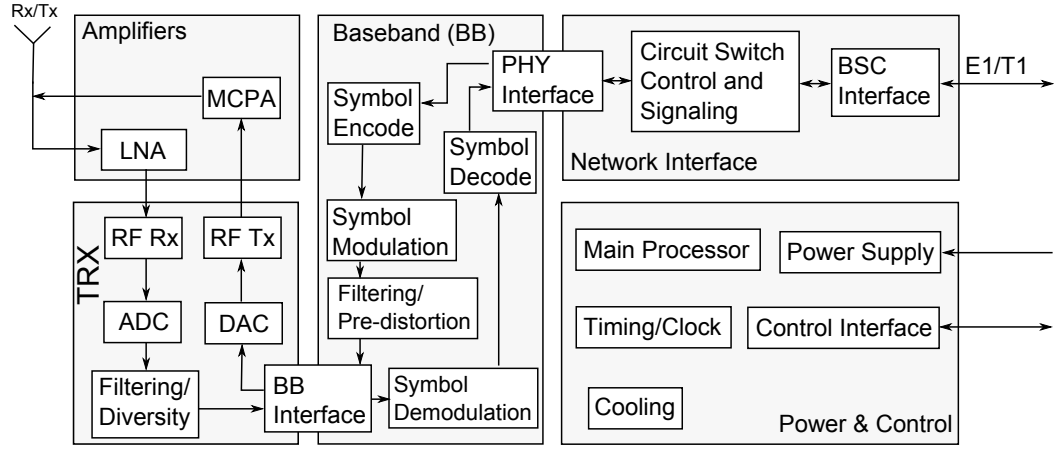


Figure 2.3: BS working diagram [1]

65% efficient, the power supply – 85%, the power amplifier (PA) a mere 45%, and last but not least feeder cables up to the antenna mast only manage to be 50% effective [52, 53]. At first look, these efficiencies are not great, but not particularly poor either. The problem arises when the complete BS is put together, which means the subsystems are interconnected, and the overall efficiency becomes the product of the individual ones. To make matters worse, these efficiencies are peak ones, which means that at lower loads, the energy consumption does not effectively scale down due to the worse performance of the components.

In light of the anticipated increase in demand for throughput in the wireless cellular networks, the overall efficiency needs to be improved. The target is to improve the overall efficiency to be over 20%, as well as improve PA efficiency to over 60%. One advancement towards this goal is locating the PA and other required electronics on the masthead to avoid cable losses as well as provide the electronics with passive cooling [1].

It is important to be aware of the current energy consumption of BSs as well as their anticipated future behaviour, so that appropriate energy efficient techniques can be designed. The current BS consumption profile is such that it does not vary significantly with the radio frequency (RF) load being experienced at the site. However, the anticipated direction for future BSs is that their energy consumption should correlate with the RF load they are experiencing [43, 54, 55]. The intention is to achieve that through improvements in the energy efficiency of the PA as well as being able to dynamically control the power state of the signal processing hardware. What this means is that techniques that decrease the number of operational BSs are appropriate for the currently deployed BS hardware, whereas the expected next generation of

BSs would work well with techniques that reduce the RF load. This thesis presents both types of techniques with an emphasis on those that will be able to work well with the future BSs.

2.3 State of the Art

This section briefly considers some of the available solutions to improve energy efficiency in current literature.

2.3.1 On energy efficiency in general

Chen *et al.* [56] define the backbone of emerging energy efficiency research and the trade-offs that are fundamental to it. The fundamental trade-offs that they have identified in the field are deployment efficiency vs. energy efficiency, spectrum efficiency vs. energy efficiency, bandwidth vs. power, and delay vs. power. The authors go on to expand on each of these trade-offs.

When speaking of deployment efficiency versus energy efficiency, Chen *et al.* bring up the process which network planning uses to raise a very important point. Deployment efficiency is measured by system throughput per unit deployment cost, whereas energy efficiency is measured by system throughput per unit of energy consumption. These two metrics due to their differences can often lead to opposite design criteria. For example, a relatively sparse network in terms of cell sites is likely to maximize the deployment efficiency, whereas a much denser one the energy efficiency in terms of RF energy per transmitted bit of data. They go on to identify heterogeneous and cooperative networks along with energy efficiency oriented user scheduling and radio resource management algorithms as promising fields of research that can bring more insight into the trade-off and potentially yield usable solutions to the design process. An important point that is not considered is that if environmental protection is to be taken into account, energy efficiency calculations need to be performed from a holistic point of view which means including both the operator and user's energy expenditure, so that solutions which simply offload the energy cost from the operators to the users are not considered as improvements over the current state of affairs.

The next considered trade-off is spectrum versus energy efficiency. This trade-off is very well understood on a link level when only the transmission power is considered. As discussed in

the article [56], the relationship is inverse. As spectrum efficiency tends to infinity, energy efficiency tends to zero. Conversely, when spectrum efficiency approaches zero, energy efficiency converges to a constant, $1/(N_0 \ln 2)$, where N_0 is the power spectrum density of white noise. The relationship becomes much more complicated when circuit power, the power used for running the hardware at the BS, as well as interference in multi-user/multicell scenarios are considered [56]. The authors suggest that smart resource allocation algorithms may be able to optimize the achievable spectral – energy efficiency trade-off. This holds true for algorithms that within the context of OFDMA are able to affect the best, or at least a better, allocation of resources to the users without explicitly manipulating the transmission powers. Decreasing interference by means other than explicitly controlling the transmission power can indeed extend the feasible space of the spectral - energy efficiency trade-off.

Bandwidth and power are usually the most demanded resources in a wireless cellular network. Unfortunately, both are in limited supply. Moreover, they are linked together by Shannon's capacity equation which creates a trade-off between them:

$$C = B \log_2 \left(1 + \frac{S}{N_0 B + I} \right), \quad (2.4)$$

where C is the channel capacity, B is the bandwidth, S is the received signal power, N_0 the noise density and I is the interference power. When considering a fixed transmission rate system, the energy efficiency benefits from expansion in bandwidth are due to the relationship between rate, bandwidth and power. However, in practical systems this relationship is not straightforward. The addition of circuit power consumption as well as filter loss, which scales with system bandwidth, makes the trade-off harder to analyze. Although the notion of bandwidth – power trade-off is well established, the authors suggest there is still a lot of room for research in the field to arrive at good solutions that consider practical systems. In essence, energy efficiency – spectrum efficiency trade-off and the power – bandwidth one are defined by Shannon's capacity equation. This means that in theory the two trade-offs should behave similarly, however in practice this is not the case as evidenced by Fig. 2 in [56].

The last trade-off identified in the paper is the delay – power trade-off. As with most of the other trade-offs, the delay – power relationship is well understood on a single link level [57]. Generally, the more delay that the system can tolerate, the more energy efficient it can be. Both channel uncertainties and random traffic are taken into consideration in [57]. However, as a result, the mathematical model is very complicated since both information theory and

queuing theory are used. The results obtained are only for a single link case. The problem is quite complex and not extensively studied, and as such it warrants further investigation. However, this topic is outside the scope of this work, as the main focus here is to enhance energy efficiency without affecting the delivered quality of service in any way.

Ferling *et al.* [54] present an overview of the goals of the EARTH project and the ways to achieve them. The project is focused on improving the energy efficiency of wireless cellular networks. The two main directions of research outlined are to access the energy efficiency potential offered by adapting to traffic statistics, and to draw upon the energy efficiency potential given by holistic joint optimizations.

Joint optimizations are defined by the authors as cross layer optimizations that take into account component and node architecture as well as radio interface technologies. Examples of such research are solutions allowing base station sleep modes, as well as the development of energy efficient radio resource management (RRM) concepts.

Adaptability to traffic statistics deviates from past research where focus is on achieving energy efficiency at peak loading scenarios. The target now is to be able to achieve high energy efficiency for all types of loading scenarios – no load, low load, as well as high load. Ferling *et al.* point out that it is important to design all solutions targeted at improving energy efficiency in such a way that they are able to adapt the energy consumption to the load level.

Three main avenues are mentioned as being able to significantly reduce the energy consumption. The first one is the improvement of transceivers to be able to scale consumed power with the actual applied transmit power such that there is a correspondence with the performance requirements. Development of radio link techniques that are able to do even more dynamic power management of transceivers, for example sleep modes, can add further enhancement to the energy efficiency. Last but not least, further additional improvements on the transceiver hardware should not only improve the correspondence between consumed and radiated power, but also the overall efficiency of the hardware.

2.3.2 Power control

One of the more straightforward ways to improve the energy efficiency of a system is through power control [58–60]. It allows the system to radiate just enough RF energy to serve its users as desired, and not waste any. Power control can hence have a profound effect on the energy

efficiency if the BS hardware energy consumption is highly correlated with the output RF power.

Shi *et al.* [61] propose a randomized power control method for two-hop interference channels which is based on mixed strategy game theory. It allows users to transmit information probabilistically, hence creating orthogonal transmission opportunities which result in interference avoidance. This in turn boosts the capacity of the system, and enhances the energy efficiency in terms of transmitted bits per unit energy. The authors show that this approach is significantly better than an existing deterministic counterpart.

Monks *et al.* [62] propose a decentralized power control algorithm using a separate control channel that is able to reduce the energy consumption of Institute of Electrical and Electronics Engineers (IEEE) 802.11 standard by a factor of 2. Xing *et al.* [63] focus on power control from a non-continuous point of view since GSM and IS-95 use a finite number of discretized power levels. They propose two discrete power control solutions based on non-cooperative game theory using stochastic utility functions. The proposed algorithms are able to perform close to the theoretical upper bound and suffer little due to the discretization.

2.3.3 Interference mitigation

Another way to improve energy efficiency is by mitigating interference. Ghimire *et al.* [64] have developed an interference mitigation approach called the Busy Burst technique, which is able to use in band signaling to reduce interference to tolerable levels in OFDMA type systems whereby the channel reciprocity offered by TDD is exploited. The demonstrated results show a significant increase in throughput compared to a benchmark system while using the same power budget. Instead, if the rate were fixed, this would lead to energy consumption savings through the reduction in required RF power.

Other interference mitigation techniques are targeted predominantly towards MIMO and cooperative systems [65]. Zhang *et al.* compare several different approaches, and show that cooperation between BSs to reduce interference can significantly increase spectral efficiency in a system with fixed power budget. As discussed above, this can directly be translated to energy savings in the case when the capacity is fixed.

2.3.4 Sleep modes

BS load varies throughout the day, hence in order to save energy it might be advantageous to turn off certain hardware components during low load periods. Han *et al.* [66] develop a theoretical model of the sleep mode included in IEEE 802.16e, and evaluate the energy savings - packet delay trade-off both theoretically and empirically through simulation. Simoens *et al.* propose a cross-layer algorithm that exploits thin client protocol information to pinpoint intervals when there is no traffic expected between the client and server [67]. In these intervals, the wireless network interface card on the thin client is instructed to enter an energy saving mode which leads to reductions in energy consumption of between 21%—52%. Wang *et al.* [68] take a different approach where in a lightly loaded LTE system the available traffic is lumped together in very few fully loaded time slots (TSs) instead of being spread over many underutilized ones. This enables the BS to not transmit any pilot signals on the remaining TSs and save RF energy. The technique allows the BS to continue to actively serve users, while enabling it to do that in an energy efficient manner. The authors claim that savings up to 90% are possible in low traffic conditions.

2.3.5 Harnessing user mobility to enhance energy efficiency

There has also been an initiative to harness mobility to enhance the energy performance of networks. Currently, most work is in the field of sensor networks due to the limited energy available to sensor devices and the need to prolong their lifetime. Ponnusamy and Abdullah [69] propose an algorithm where sensor nodes are subdivided in two types – static and mobile. The mobile nodes act as routing agents to increase network lifetime by traveling between the static nodes to collect the sensed data and then deliver it to the BS. Moreover, the authors propose that the mobile nodes also harvest energy to further increase the lifetime of the network. Unfortunately, they do not provide any empirical results on the energy saving expected. Ekici *et al.* [70] make a comparison between the already existing schemes that utilize mobility to enhance the lifetime of wireless sensor networks, and then go on to propose a novel algorithm on how to compute a more effective trajectory for the mobile nodes, or as they refer to them – mobile platforms. The prior approaches can be classified in three main groups – mobile BS approaches, mobile data collector ones, and rendezvous ones, which are a hybrid of the first two. Their proposed solution to the path computation for the mobile platform is called the Multihop Route to Mobile Element algorithm. It computes periodic

paths for the mobile platform to avoid sensor data loss and reduce the speed of travel of the platform itself. The speed of the mobile platform is directly proportional to the energy it uses to travel. Simulation results show that the proposed algorithm is able to reduce the speed of the mobile platform significantly over other solutions and achieve a negligible message loss rate, hence improving the energy efficiency of the system. Kolios *et al.* [33] take the concepts mentioned in [69,70] and apply them to a wireless cellular network to trade-off delay for energy efficiency. Their scheme termed Mechanical Relaying is based on the idea of store carry and forwarding in a cellular network, where the mobility of each user is utilized to explore the long term evolution of their link gains. The technique is evaluated both analytically and numerically. Depending on the delay tolerance of the desired service, the technique is able to provide reductions in energy use up to multiple orders of magnitude.

2.3.6 Resource allocation

In the past, resource allocation has been considered primarily as a means to increase the spectral efficiency of networks, as well as make sure that users are treated fairly and receive a reasonable share of the available system resources [71, 72]. Kim *et al.* [71] extend the well known proportional fair scheduler to a multicarrier system and investigate its performance. The multicarrier implementation that is proposed by them is able to grant comparable results to a round robin system and a system that applies the proportional fair (PF) principle on each carrier separately in terms of long term throughput. Moreover, the proposed system performs better in terms of latency. Moretti *et al.* [72] propose a distributed resource management technique that is able to achieve high spectral efficiency and throughput fairness among flows in a multicell multicarrier system. A byproduct of the technique's goal to reduce interference, in order to boost spectral efficiency, is that it is able to outperform the benchmarks it is compared to in terms of required power to achieve a certain spectral efficiency.

As the research in [72] shows, energy efficiency is not necessarily always traded off for spectral efficiency, it can also be improved by reducing interference for example. Bhatia *et al.* [73] attempt to solve the joint, routing, scheduling and power control problem in a multi-hop wireless network. They derive a polynomial time 3-approximation algorithm to solve the problem. The algorithm is able to provide feasible solutions as well as what the lower bound in terms of required energy to achieve a certain rate between two nodes is. Their solution is also extendible to several nodes communicating simultaneously over the same network.

Meshkati *et al.* [74] use a game-theoretic model to study the problem of joint power and rate control with quality of service constraints in a multiple access wireless network. The quality of service constraints are specified as an average achieved rate at the source, and a delay constraint which includes both the transmission and queue delays. The utility function used in order to achieve energy efficiency measures the number of reliable bits transmitted per joule of energy used. The Nash equilibrium solution to the non-cooperative game is found. The authors demonstrate that the presence of users with strict quality of service constraints significantly undermines the network capacity and energy efficiency as these users require more system resources to be served.

In [75], the authors develop algorithms to minimize the energy required for data packet transmission in a wireless environment. The algorithms are based on the principle of extending the duration of transmissions in order to save energy *i.e.* using lower order, more energy efficient modulation schemes. The authors first solve the problem in an offline manner, and then modify their proposed algorithm to be more computationally efficient and applicable in an online manner. It is noted that the required queue knowledge does not need to extend very far in the future for the online algorithm to perform close to its offline version. However, it is prudent to note that trading off delay for energy efficiency is not necessarily always desirable.

Zhang *et al.* [76] also take the route of jointly allocating bandwidth and power in order to improve the energy efficiency in a multi-user system. The authors consider circuit-level modeling of the energy consumption in order to simulate the real operating environment as closely as possible. This means that energy consumption not only depends on the used RF transmission power, but also on the used bandwidth. Zhang *et al.* propose an allocation algorithm based on bi-section search over the space of solutions. Their solution is able to outperform a uniform system that gives each user the same share of the available resources in a 4 user scenario.

2.3.7 Channel modeling

When designing techniques to improve energy efficiency and testing them in simulation to gauge their performance, it is also important to use the best available channel models, so that the obtained results are as close to reality as possible. Narandzic *et al.* [77] test against each other the 3GPP spatial channel model (SCM) and spatial channel model extension (SCME) models, as well as models developed by Wireless World Initiative New Radio (WINNER).

The authors find that the WINNER models' strength lies in scenario-customized parameters based on real channel measurements. However, when system parameters deviate from the pre-defined scenarios, the WINNER models are theoretically unable to offer ways to accurately support those changes. Whereas SCME has some built-in capabilities to do that, and that is its main strength. Another advantage that the WINNER models have is that they reproduce observed correlations of large scale parameters, parameters that govern the time dependent change in low-level channel parameters in order to simulate the channel's non-stationary behaviour, at link and system level. Overall, the authors suggest that the better support for higher bandwidth scenarios of the WINNER models makes them a favorite at the time of publication.

2.3.8 Link capacity

Once the scenario is known for a system simulation, it is important to know what the system is capable of on a link level. When a system level simulation is performed, most often the link level is not simulated but results from a link level simulator are used to reduce computational complexity. In their work, Mogensen *et al.* [78] compare the LTE capacity to the well known Shannon bound on capacity. They find that under ideal channel knowledge and additive white Gaussian noise (AWGN), on a link level LTE is able to perform approximately 2 dB away from the Shannon capacity. This finding is later used in this work to be able to generate a meaningful modulation table for LTE. The deviation becomes much larger when a typical urban fading channel is used. The authors also introduce a technique using a modified Shannon formula that allows quick prediction of the capacity of LTE systems for realistic deployment scenarios.

In their work, Simulating the Long Term Evolution Physical Layer, Mehführer *et al.* [79] also compare the performance of LTE to that predicted by Shannon's capacity formula. They find that the signal-to-noise ratio (SNR) gap between the theoretical capacity and the one achieved by their simulation of the LTE physical layer is approximately 2 dB. This result matches the aforementioned one by Mogensen *et al.*.

2.3.9 Energy efficient scheduling

The last topic discussed in the review of the state of the art is that of energy efficient scheduling since it is the focus of most of this thesis. Energy efficient scheduling has emerged only

relatively recently within the realm of cellular networks. Previously the focus has been on scheduling that provides fairness between users as well as maximizes the spectral efficiency. Extensions of the well known round robin and proportional fair schedulers focus on achieving exactly that [80–85].

The topic of energy efficient scheduling has previously been discussed widely in wireless sensor networks [75, 86]. However, most of the work is in the context of relaxing quality of service constraints for energy efficiency. Within the traditional multi-cell literature, the main topic of research is achieving higher spectral efficiency with an additional emphasis on fairness among users [72]. The focus is moving to increasing the energy efficiency of BSs towards that of mobile terminals. Han *et al.* [87] compare several schedulers in terms of throughput, fairness and energy efficiency. Their proposed fair cluster algorithm is focused on providing fairness over the user population but is also able to deliver energy efficiency improvements of about 12% compared to a round robin (RR) benchmark. The other proposed greedy algorithm, provides a 10-fold reduction in used energy, unfortunately at the expense of a detrimental reduction in both throughput and power fairness as measured by an adaptation of Jain’s fairness index. Yao *et al.* [86] have proposed an energy efficient scheduling algorithm based on non-uniform time division multiple access (TDMA) that varies transmission length based on channel state and the size of the transmitted information. Their scheduler is able to achieve a reduction in used energy of up to 80% at the cost of longer transmission times.

Jones *et al.* [88] present a comprehensive survey of energy efficient scheduling techniques. Unfortunately none of the presented approaches are able to deal with real time data transmission constraints, as well as able to guarantee no adverse effects to the users’ delivered quality of service. Chen *et al.* [89] consider the problem of energy efficient scheduling of packet transmission duration with individual packet delay constraints. They propose an optimal offline scheduler, as well as two online versions of it. Unfortunately the authors have constricted themselves in solving the problem of the optimal packet transmission time without any consideration of multiple access phenomena as well as the more general problem of allocation of frequency-time resources in wireless systems. Moreover, there is no comparison with any well known schedulers so that the performance of their proposed solutions can be properly assessed. A number of other researchers have also considered a similar problem [90–93].

Clearly, there is a gap in the existing research which allows for the development of not only energy efficient scheduling algorithms, but algorithms that can minimize energy expenditure

without any decrement to the experienced quality of service by the users. Moreover, by jointly considering the allocation of frequency, time and power resources the ability of the system to achieve energy efficiency gains is maximized. It is the goal of this thesis to contribute in filling the aforementioned gap in available schedulers in literature.

2.4 Summary

In this chapter, a short summary of the history of wireless cellular communications is presented. Required metrics for the measurement of energy efficiency of the systems that are to be evaluated are introduced. The concept of OFDMA is briefly explained, as it is to be at the foundation of the evaluated 4G system in this thesis. A quick introduction is made to the different subsystems that are the main sinks of energy in a BS. Lastly, state of the art techniques are introduced that can be used to reduce the energy consumption of wireless cellular networks and are critically discussed.

This thesis will focus on introducing techniques in the next two chapters, mostly in the realm of scheduling, that are able to achieve energy efficiency and throughput gains with no to little detriment to the other performance metrics in the system. The last technical chapter introduces a hardware power state control algorithm which again tries to achieve energy consumption reduction with no effect on the perceived quality of service on the user side.

Having established the background with this chapter, Chapter 3 introduces the first technical contribution, the energy efficient score-based scheduler (EESBS).

Chapter 3

Energy Efficient Scheduling

SHEDULING is the process through which resources are allocated to users within a wireless cellular system. These resources might be represented by slots in time and/or well defined frequency bands. When the system in question is an orthogonal frequency division multiple access (OFDMA) one, then a resource is both – a time slot on a frequency band *i.e.* a user is allowed to use a frequency resource block (RB) at a particular time. Scheduling can have a significant effect on the achieved data rates and energy efficiency due to the resulting interference, as well as the underlying path gains on each different RB. In particular, frequency selective fading, a common phenomenon in wireless communications, can create tremendous opportunities that can be exploited by smart schedulers. For example, deep fades experienced on certain frequency channels are not simply something that needs to be avoided, but are also an opportunity for nearby users who are not experiencing such unfavorable channel conditions to use those frequency channels without generating intolerable interference. Hence, an energy efficient communication system should have at its heart a scheduler which is aware of the concept of energy efficiency and promotes it.

The rest of this chapter is structured as follows. Section 3.1 introduces the already known concept of score-based scheduling. It is followed by Section 3.2 which describes the process through which the score-based scheduler is modified to arrive at the novel energy efficient score-based scheduler (EESBS) system. Section 3.3 delves into the difficulties of theoretical modeling. The simulation set-up used for empirical testing is described in 3.4. The results from the simulations are presented in Section 3.5. The chapter concludes with Section 3.6.

3.1 Score Based Scheduling

The concept of score based scheduling is first put forth in [94]. A score based scheduler is designed to behave like a proportional fair (PF) scheduler in the ideal case, but not to suffer

performance losses from asymmetric fading or data rate constraints. In principle, the score based (SB) scheduler assigns a time slot (TS) t to the user $j(t)$ with the best score:

$$j(t) = \arg \min_{j=1,\dots,n} s^j(t), \quad (3.1)$$

where the score $s^j(t)$ of user j at slot t corresponds to the rank of its current transmission rate $R^j(t)$ among the achieved past values $\{R^j(t), R^j(t-1), \dots, R^j(t-W+1)\}$ which are observed over a window of size W . The user with the lowest rank is selected for transmission at any given time. Formally, the score $s^j(t)$ is calculated as:

$$s^j(t) = 1 + \sum_{l=1}^{W-1} \mathbb{1}_{\{R^j(t) < R^j(t-l)\}} + \sum_{l=1}^{W-1} \mathbb{1}_{\{R^j(t) = R^j(t-l)\}} X_l, \quad (3.2)$$

where $\mathbb{1}_{\{\cdot\}}$ is the indicator function which returns 1 if the condition in the curly brackets is true and 0 otherwise, and X_l are i.i.d. random variables on $\{0, 1\}$ with $\Pr(X_l = 0) = 1/2$.

The SB scheduler selects a user when its potential transmission rate is high relative to its own rate statistics, rather than when the transmission rate is high relative to its own average throughput, which is what a PF scheduler does. By doing this the effects from asymmetric fading and data rate constraints are circumvented and the PF type behaviour is conserved in the ideal case [94].

3.2 Energy Efficient Score Based Scheduling

The SB scheduler in its basic form outlined above cannot directly be used to enhance energy efficiency. The metric used for rating the resources needs to be changed, as well as the whole approach, which has to be adapted to OFDMA rather than time division multiple access (TDMA) systems.

Just as in a TDMA system, RB allocation needs to be done and updated at a regular period to keep up with the channel conditions – for example every Long Term Evolution (LTE) sub frame, which is 1 ms long. In theory, the shorter the time span for which resources are allocated, the better the energy efficiency would be. This is due to less time being allowed for the channel conditions to change. However, in practice the re-allocation of resources carries some additional energy overhead due to control signaling as well as circuit energy due to the

additional computations. This means that a balance between allocation time and consumed energy during allocation needs to be found.

To promote energy efficiency, RBs that can be used in a highly energy efficient manner need to be allocated first. This can be achieved by using a metric to rate the RBs that measures the energy efficiency. A large number of metrics can be used – total energy used, energy per bit delivered etc. In this work, total radio frequency (RF) energy emitted by the antenna at the BS is chosen. By using this metric, the total energy consumption is minimized. The reduction in output RF energy should also help reduce interference. While the metric is not a measure of the total energy used by the base station (BS), it is a measure of the energy that scheduling has control over.

Another consideration that has to be made is regarding the way the scores are calculated over the RBs. In general there are three possibilities – calculate relative scores on all RBs for each user at a time, calculate relative scores on a single RB for all users, or calculate absolute scores between all users and RB combinations. The last option results in the scores being an absolute measure of the energy efficiency performance of each user and RB combination. An illustration of the different processes can be found in Fig. 3.1. The shading represents the space over which the scores are computed. For example, when the scores are calculated relative for each user, that means the score each RB receives is relative to the performance of the other RBs from the perspective of that user. When the scores are calculated relative to the RB, the users are practically ranked according to the efficiency with which they can transmit on that RB. Finally, when the scores are calculated over all users and RBs, the user and RB combinations are ranked according to their energy efficiency against all other such combinations. Calculating the scores relative to each user, allows each user to optimize their energy performance, whereas computing them over the complete space of RBs and users allows for the optimization of the energy consumption of the complete system. The second method, relative to each RB, is a compromise between the two.

Within this work, the first, relative to user, method is used. It provides the highest degree of energy efficiency fairness between the users, and does not pose any additional difficulties when it comes to data rate fairness. If RBs are allocated based on their scores between users, and those scores are calculated either on a global scale or on a RB scale, users with better channel conditions will be favored above all others. This will lead to a skewing of the achieved data rate allocation.

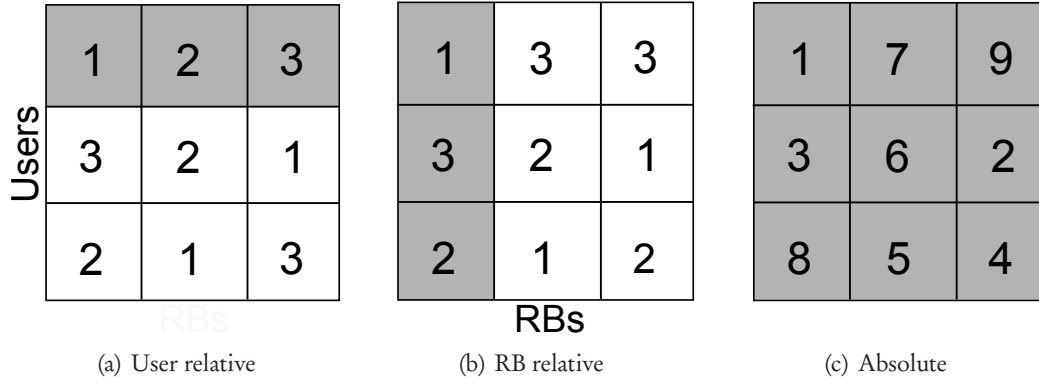


Figure 3.1: Score calculation options in EESBS

Fairness among users in terms of achieved data rate is also a priority built in the design of the scheduler. To ensure that, all users are allocated one RB at a time until their service requirements are met. By doing so, the effect that high demand users have on low demand ones is minimized. High demand users are allocated resources at the same rate as lower demand ones. The total number of users in the system becomes more important rather than the existence of high demand users, assuming all users are given the same priority. Please note the distinction between high priority and high demand users. High priority users will always have a detrimental effect on fairness in the system. This is due to the fact that they will always be allocated resources regardless of the requirements of the remaining users. In a sense, the high priority users exist in a system with the complete RB pool available to them and no other users. The remaining non-priority users perceive the system as having fewer RBs available for allocation due to the effected priority user RB allocation. As a result, they experience a performance gap between themselves and the priority users.

The equation for calculating scores hence becomes:

$$s_q^j(t) = 1 + \sum_{k=1, k \neq q}^M \mathbb{1}_{E_k^j(t) > E_q^j(t)} + f^j(m_j), \quad (3.3)$$

where $s_q^j(t)$ is the score for RB q for user j at TS t , $E_k^j(t)$ is the energy metric evaluated for user j on RB k at t , M is the total number of RBs and $f^j(m_j)$ is a penalty function based on the number of already allocated RBs for the user. Lower scores indicate more desirable RBs. The energy metric and penalty function are defined as $E_k^j(t) = P_k^j(t)$, where P_k^j is the RF transmission power required on RB k for user j , and $f^j(m_j) = m_j$ respectively. It is in theory possible to assign each user a separate penalty function, as well as to have a penalty

function that prioritizes users based on different criteria, such as vulnerability, subscription plan etc. This makes the EESBS a versatile and easy to tailor scheduling technique.

A pseudo code implementation of EESBS can be found in Algorithm 1. The **RESOLVE** clause represents the process through which conflicts between users are settled. Since, EESBS does not have a random component in the score calculation, it is possible to arrive at situations where two users have the same relative score on a RB. A conflicting RB is allocated to the user who needs the least amount of energy in absolute terms to use it, whereas the rest of the users are allocated their next best RB according to the calculated scores. This process supports the principle of fairness in the system.

Algorithm 1 Amended score-based scheduler

```

INITIALIZE requiredResources(1...j)  $\leftarrow$  calculate number of required RBs for all users
while sum(requiredResources) > 0 do
  CALCULATE  $s_q^j(t) = 1 + \sum_{k=1, k \neq q}^M \mathbb{1}_{E_k^j(t) > E_q^j(t)} + f^j(m_j)$  for all users and RBs
  for i = 1 to number of BSs do
    FIND best RB for each user connected to this BS based on  $s_q^j(t)$ 
    if User's best RB is not allocated AND is usable AND is not another user's best RB then
      ALLOCATE RB to user
    end if
    if There were conflicting RBs between users then
      RESOLVE conflicts by allocating RB to most efficient or priority user
      ALLOCATE next best RBs, based on  $s_q^j(t)$ , to the remaining users
    end if
  end for
  if There are no available RBs for allocation then
    EXIT while loop
  end if
end while
RUN power control algorithm

```

The last step in the scheduling algorithm is to run a power control subroutine. Power control is necessary to ensure that the minimum feasible transmission powers can be calculated, which allows the proposed techniques to be correctly evaluated. This ensures the most efficient operation of the system. The algorithm of choice here is the Foschini-Miljanic power control algorithm [95] due to its simplicity, low computational overhead and ability to achieve pareto

optimal results. It is based on the following iterative control equation:

$$P_q^j(t) = \frac{\Gamma_q}{\gamma_q^j(t-1)} P_q^j(t-1), \quad (3.4)$$

where $P_q^j(t)$ is the transmission power used for user j on RB q for TS t , Γ_q is the signal-to-noise-plus-interference ratio (SINR) target for RB q , and $\gamma_q^j(t-1)$ is the achieved SINR at the time instance prior to this one. The power control subroutine should be allowed to run until the difference in the transmission power vector for each BS between iterations, ϵ , has converged to a preset value. Within this work, ϵ is defined to be 0.1% of the maximum BS radio frequency transmission power. The particular implementation used in this thesis corresponds to the power control algorithm outlined in the original paper [95] with parameter $\beta = 1$. The convergence results presented in the paper indicate that on average 5 loop iterations are required to get 6 users to within 1% of their SINR targets. The scenario used in this thesis leads to a number of significant interferers on a single RB that is less than 6 due to the number of neighbouring cells. Although the convergence target is more demanding at first glance, the number of control loop iterations remains low – empirical results show an average between 6 – 7. It is important to note that it is difficult to compare the 1% target used in the paper with the 0.1% target used here, as one measures the distance from the target, and the other the change in the transmission power vector.

Due to the use of power control, the transmission powers used to calculate the energy efficiency metric used for allocation will be different from the ones actually used for transmission. This will result in a difference between the expected energy efficiency at allocation and the achieved one. Since even the single channel scheduling problem is NP-hard [96], a heuristic solution is proposed for energy efficient allocation of RBs and power to transmit on them. Within this framework, each allocation iteration improves on the energy efficiency of the system. This solution does not necessarily attain a global minimum but improves on the allocation with each iteration.

3.3 Analytical Model

Unfortunately, the problem is so complex that an analytical solution is very difficult to construct. The problem lies with the coupling between users that exists due to interference. Moreover, users connected to the same BS are distributed resources from the same pool, which also

adds another level of coupling between them. What is even more important is that the two levels of coupling affect each other *i.e.* a change in the allocation affects the received interference, and a change in the received interference has an effect on the resource allocation in the system.

What this means is that any analytical model of the scheduling process will come down to a tightly coupled system of equations. Interference is highly dependent on the instantaneous channel conditions as well as the position of the users within the served area. All of this means that any analytical model that is constructed will be so complex that it will require a computation platform to produce results almost as complicated as the simulation outlined below. Moreover, it is likely that the solution will not be a closed form one, which means that the analytical model might not be able to provide significant additional information.

3.4 Simulation System Set-up

To validate the performance of EESBS and the other scheduling techniques proposed in this thesis, a simulation platform is used to evaluate their performance against a frequency selective proportional fair (FsPF) scheduler as the one discussed in the Problem Formulation section of [97]. The overall system framework is modeled after LTE – it is an OFDMA based system with parameters taken from the LTE standard proposal documentation.

The simulation parameters employed can be found in Table 3.1. Each user is assigned a target data rate from a uniform distribution comprised of the following elements – $\{0.5, 1, 1.5, 2\}$ Mbps for low load scenarios and $\{2, 3, 4, 5\}$ Mbps for high load ones. Also, the number of users is varied between the high and low load scenarios. In the low load case, each BS gets between 5 and 9 users, and in the high load case – between 10 and 19. The number of users coupled with their required datarates result in a bandwidth loading between 20 – 50% for the low load case and between 50 and over 100% for the high load one.

RBs that cannot be used for transmission due to experiencing temporary deep fades or high path loss are not considered during the process of allocation, as any attempt at communication on them would fail anyway.

The user specific penalty function used within the EESBS scheduler is as defined previously. This means that the more RBs are allocated to a user, the larger the penalty resulting in a fairer

Table 3.1: *System Parameters*

Parameter	Value
Total Bandwidth	20 MHz
Carrier Frequency	2.14 GHz
Resource Bandwidth	180 kHz
Number of Resource Blocks (RBs)	100
Subcarriers per RB	12
Time slot duration	0.5 ms
OFDM symbols per TS	7
BS Maximum Power	46 dBm
User Speed	3 km/h
SINR targets, Γ_q	-6 – 20 dB
Data rates	0.1655 – 5.9174 bits/symbol
Users per BS	5 – 9; 10 – 19
Required data rate per User	{0.5, 1, 1.5, 2} or {2, 3, 4, 5} Mbps
Inter-site distance	870 m
Overhead	12.9, 26.9%
Control channel SINR target, Γ_{ref}	3.4 dB
Antenna gain	14 dB
Number of harmonics, K	10

allocation. The current resource allocation and channel conditions are used to estimate the required energy within the scheduler.

The downlink transmission direction is simulated as it is currently the more energy intensive of the two. This is due to the fact that generally content consumption is a lot higher than content generation in end user mobile devices. Data is collected from one time slot after the system has settled to a stable resource allocation. Stability of resource allocation is important since it is desirable that RBs can be used by a user continuously, rather than be constantly contended for by a number of users. Channel condition changes are to be accounted for at the same time. In a practical system, resource allocation stability can be disturbed when a more efficient allocation becomes available due to a change in channel conditions.

In general, the simulator starts by allocating the BSs and users locations in space. The BSs have predefined locations, and the users are distributed according to the scenario distribution in space. This is followed by the channel generation as well as the generation of required data rates per user. The different scheduling algorithms to be evaluated are then run together with the power control algorithm until stable resource allocations are achieved. Performance statistics are then collected from the central BS in the scenario to ensure the most realistic

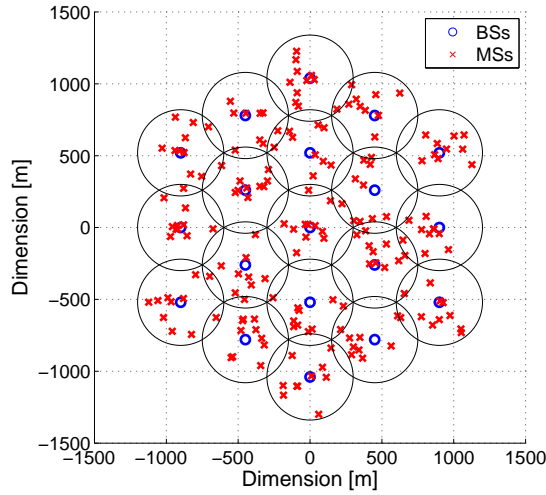


Figure 3.2: *Example simulation scenario realization*

environment as well as reduce edge effects. Below, the different steps involved in the simulator are considered in more detail.

3.4.1 Scenario

The scenario considered is a two tier wrap-around a central cell. This scenario is recognized as one that generates realistic interference conditions in the central cell. An example random realization can be found in Fig. 3.2.

All BSs are operated in the same manner by utilizing the system that is being evaluated. Results are only collected from the central BS to make sure that they are as realistic as possible and keep edge effects to a minimum. Fig. 3.3 presents the distribution of interference per RB as a function of the number of tiers simulated. While there is a difference of approximately 1.7 dB between the two curves, their behaviour overall is similar. Moreover, the range of values that the interference takes on is the same, only their distribution among the users slightly different. While the interference distribution achieved with 3 tiers is likely more realistic than that achieved with 2 tiers, it certainly does not warrant the approximately 10 times increase in computational time. It is important to keep in mind that a difference of 1.7 dB represents a difference in link distance of several meters at the cell center and up to approximately 40 at the cell edge according to the channel model as presented in Table 3.2 below. The 2 tier scenario strikes a balance between realistic interference distribution and reasonable computa-

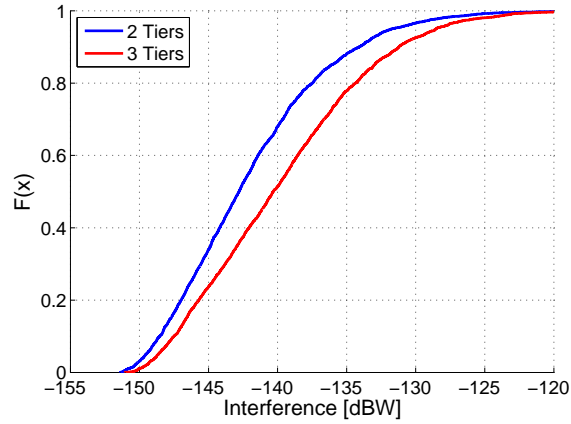


Figure 3.3: *Interference distribution for different number of tiers*

tional time that allows different system configurations to be investigated.

Users are distributed uniformly in each cell area. This means that if user distribution were plotted as a function of distance, there would be more users at the cell edge than in the center of the cell. However, each cell is randomly assigned a number of users to be allocated from a pre-defined discrete uniform distribution. If the distribution is defined as $\mathcal{U}(a, b)$, where a is the minimum number of users and b the maximum, then a uniformly distributed integer random number of users between a and b are uniformly distributed within the coverage area of a BS.

3.4.2 Channel models

The slow fading channel model used is the LTE urban micro cell (UMi) [98] as defined in Table 3.2, where d is the distance between transmitter and receiver, f_c is the carrier frequency in MHz, h_{BS} is the elevation of the base station BS antenna, and h_{UT} is the elevation of the user terminal antenna. The top equation for line of sight (LOS) conditions is used for d between 10m and the breakpoint distance, and the lower one for distances higher than the breakpoint distance but less than 5km. The breakpoint distance is calculated as $d_{BP} = 4h_{BS}h_{UT}f_c/c$.

The probability of LOS is given by:

$$\Pr_{LOS} = \min(18/d, 1)(1 - \exp(-d/36)) + \exp(-d/36) \quad (3.5)$$

The fast fading channel model used is based on Schulze's method [99] while making use of

Table 3.2: *Channel Model*

	Path Loss [dB]	St. dev. [dB]
LOS	$L = 22 \log_{10}(d) + 28 + \log_{10}(f_c); 10 < d < d_{BP}$	$\sigma = 3$
	$L = 40 \log_{10}(d) + 7.8 - 18 \log_{10}(h_{BS} - 1) - 18 \log_{10}(h_{UT} - 1) + 2 \log_{10}(f_c); d > d_{BP}$	$\sigma = 3$
NLOS	$L = 36.7 \log_{10}(d) + 22.7 + 26 \log_{10}(f_c)$	$\sigma = 4$

the parameters proposed by WINNER in their clustered delay line model [100]. The impulse response of the channel is calculated using:

$$f(\tau, t) = \sum_{n=1}^K p_n e^{j(\theta_n + 2\pi f_{Dn} t)} \delta(\tau - \tau_n), \quad (3.6)$$

where p_n is the power and τ_n is the delay of the particular zero delay-spread cluster (ZDSC) taken from the WINNER standard, θ_n is a uniformly distributed random variable defined in $[0, 2\pi]$, K is the number of different path components considered, f_{Dn} is the maximum Doppler frequency, and the index n stands for the position of the ray in the sequence of arrival. Afterward, a fast fourier transform (FFT) is performed on the impulse response, as well as normalization with respect to power, to obtain the frequency selective fading of the channels. The line or non-line of sight conditions are taken into account while generating the fast-fading characteristic. There are separate sets of power and delay profiles for LOS and non-line of sight (NLOS) conditions. An example channel realization can be found in Fig. 3.4.

Channels are generated for every possible link in the system in the downlink direction. This is done to facilitate the interference calculations which consider interference that each user receives from all BSs in the deployment scenario. Interference on a RB q for user j is calculated as:

$$I_q^j = G_{\text{antenna}} \sum_{i=1}^{n_{BS}} P_q^i G_q^{ij}, \quad (3.7)$$

where P_q^i is the transmission power on RB q for BS i . Of course, the transmission power from the BS that user j is connected to is disregarded in the above calculation as it forms the desired signal and not part of the interference.

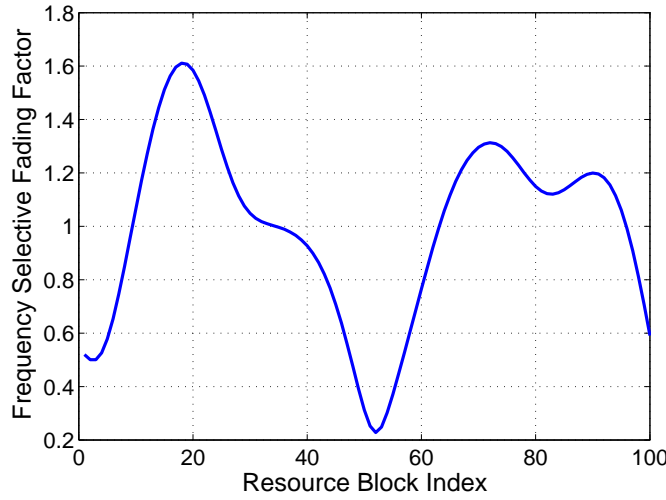


Figure 3.4: Example frequency selective fading realization

3.4.3 BS hardware models

Three versions of the same model are used throughout this work. The BS power consumption model is the one adopted in [55]. It is governed by the following equation:

$$P_{BS,in} = P_{BS,0} + \Delta_p P_{BS,out}, \quad (3.8)$$

where $P_{BS,in}$ is the required power drawn by the BS in Watts, $P_{BS,0}$ is the idle power consumption *i.e.* when no RF power is used for data transmission, also in Watts, Δ_p is a scaling parameter that represents the efficiency of the RF hardware, and $P_{BS,out}$ is the required output RF power in Watts. The maximum value allowed within this model for $P_{BS,out}$ is $P_{BS,out}^{\max}$ which would generally be a design parameter of the BS. The appropriate parameters for a macro BS are $P_{BS,0} = 712$ W, $\Delta_p = 14.5$, and $P_{BS,out}^{\max} = 40$ W [55]. A plot of the required input power over the range of operation can be found in Fig. 3.5. This model reflects the current state of BSs.

It is expected that the efficiency of BS hardware will improve in the near future as outlined in the introduction and background chapters. Also, input power requirements should scale much better with the required output RF power as power amplifier (PA) efficiency is improved and the overall BS consumption reduced [43]. It is expected that as BSs efficiency is improved, the dynamic component of BS energy consumption will become increasingly dominant over the quiescent drain hence increasing the benefit from energy efficient scheduling techniques that reduce the RF power consumption. This is why two additional consumption models

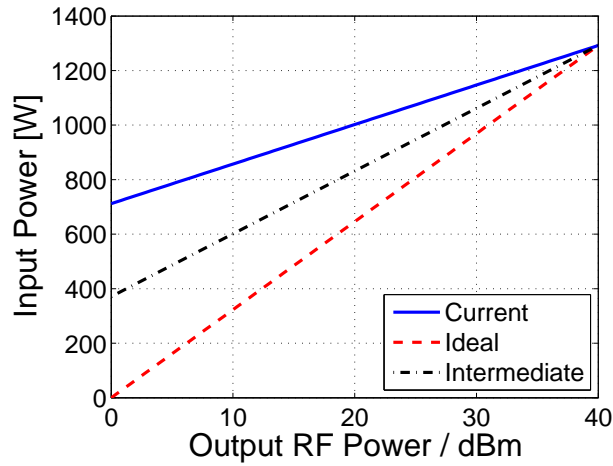


Figure 3.5: BS hardware energy consumption model

are proposed and adopted. One models the desired ideal performance of the future BS, and the other represents a more realistic proposition. The second model is more realistic as it is an improvement over the current BS consumption model, but still represents a BS that has a non-zero quiescent state energy drain. Both models can be expressed in the same manner as (3.8). The parameters for the intermediate model are $P_{BS,0} = 371$ W, $\Delta_p = 23.025$, and for the ideal one – $P_{BS,0} = 0$ W, $\Delta_p = 32.3$. The maximum output RF power remains the same, as well as the peak energy consumption. The two additional models do not represent an improvement of peak load efficiency. They differ by having a lower quiescent energy drain. The combination of the same peak load energy efficiency and lower quiescent drain means that these models actually represent a worse RF chain efficiency. However, the additional models exhibit a better correlation between input power required and BS RF power load. It is this behaviour that should be evaluated together with any proposed algorithms in order to gauge how future hardware could work with them. An increase in the efficiency of the RF chain will simply translate in overall energy reduction, and should not negatively affect any techniques targeted at achieving energy savings.

The first, pessimistic, model is used for theoretically evaluating all proposed techniques in this work. This gives a more realistic view on the gains as the theoretical results make use of idealistic assumptions leading to high predicted gains. However, all three models are used to evaluate the energy savings through simulation.

Overall, the three models have peak energy efficiency of 3.1%. If we were to compare that

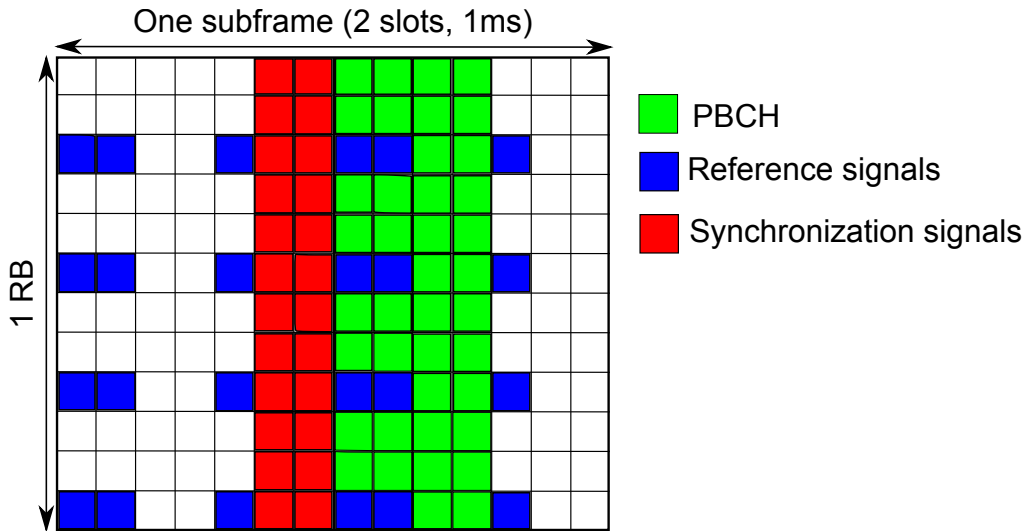


Figure 3.6: *PBCH allocation*

to the values presented in Chapter 2, the models outlined above represent a slightly older generation of BS hardware. It is also important to note that the ideal model described above is ideal in terms of the correlation between input and output power, and not in terms of the energy efficiency of the RF hardware.

3.4.4 Overhead model

Typically, cellular systems have a broadcast channel which carries information that allows the other channels in the system to be configured and used for communication. The 3rd Generation Partnership Project (3GPP) LTE makes use of a physical broadcast channel (PBCH) which carries a master information block (MIB), as well as a physical downlink control channel (PDCCH). Both are a part of the physical downlink shared channel (PDSCH) – and are allocated particular resources in time and frequency [45].

This work assumes that the PBCH, reference, and synchronization signals are transmitted with constant power, so that they can achieve coverage of the complete intended cell site. PBCH information is transmitted every 40 ms or every 40 sub-frames. In addition to that, in every sub-frame there is PDCCH data as well as reference signals that are transmitted. The PDCCH data can be configured to occupy the first 1, 2, or 3 orthogonal frequency division multiplexing (OFDM) symbols.

If we are to quantify the total overhead due to PBCH and PDCCH, which is henceforth

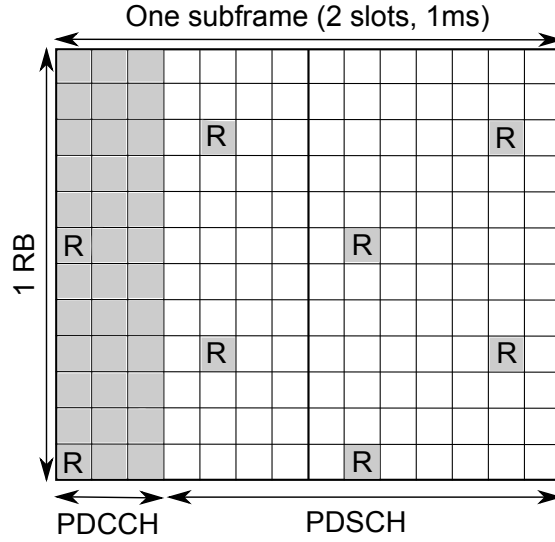


Figure 3.7: PDCCH allocation

referred to as ϕ , using the values presented above, calculations show that it varies between approximately 12.9% and 26.9% [45]. It is important to note that this is overhead both in terms of communication time and energy. The contribution of PBCH is relatively minor – approximately 1.3% relative to the complete system. Of course, there are also other types of overhead that are not considered here – for example physical control format indicator channel (PCFICH) and physical hybrid ARQ indicator channel (PHICH). These do not constitute a significant part of the control channel overhead in the system. It is also important to note that the PDCCH could potentially be turned off if the particular frequency resource blocks are not going to be used, whereas the PBCH cannot be turned off as it is required so that new users can connect to the network. Hence, only the overhead from the PDCCH will be considered.

The following assumptions are made throughout this work. The PDCCH along with the reference signals can be turned off if the particular RB is not in use until the next allocation cycle. This means that the control channel overhead due to PDCCH can be modeled as a transmission that occupies a fraction of the TS at a constant pre-set RF power when the RB is in use. This assumption is in line with the already introduced in LTE technique of almost blank subframe (ABS) [101].

In light of the above, the control channel transmission power, P_{ref} , has to be defined in a meaningful manner. Control channel transmissions need to be able to reliably reach any user

within the radius of the BS. Hence, P_{ref} needs to be defined with respect to the cell radius, r , and an SINR target, Γ_{ref} , that defines the modulation used for control channel communication. The following equation is used to calculate the required control channel transmission power per RB:

$$P_{\text{ref}} = \frac{\Gamma_{\text{ref}}(N + I_{\text{max}})}{G_{\text{min}}(r)G_{\text{antenna}}}, \quad (3.9)$$

where $G_{\text{min}}(r)$ is the worst path gain at the cell edge, calculated using the NLOS equation in Table 3.2, between the user and BS including log-normal shadowing up to two sigma away from the mean as that covers 95% of the user population. When the cell radius is set at 500 m, $G_{\text{min}}(500)$ is -134.34 dB. I_{max} is the worst interference a user at the cell edge can experience on a single RB and G_{antenna} is the antenna gain. The maximum interference is calculated as:

$$I_{\text{max}} = P_q^{\text{max}} G_{\text{min}}(r) G_{\text{antenna}} = 3.67 \cdot 10^{-13} \text{W}, \quad (3.10)$$

where P_q^{max} is the maximum transmission power per RB. P_q^{max} is calculated by dividing the maximum output RF power of the BS by the number of RBs in the system. The interference is the maximum possible for the given scenario with the parameters used in Table 3.1 and the employed channel model.

3.4.5 Modulation schemes

The data transmission SINR targets are chosen using Shannon's channel capacity equation by adding an additional 3.5 dB to the calculated SINR targets. This is a reasonable assumption since two independent studies have determined that LTE achieves link level spectral efficiency that is on average 2 dB away from the Shannon limit [78,79]. This guarantees that the values used are reasonable and close to the current state of the art.

3.4.6 Benchmark

The FsPF scheduler operates by applying the proportional fair principle to each RB at a time, and allocating each RB to the user who maximizes the fairness ratio. Let $\lambda_q^j(t) = r_q^j(t)/R^j(t)$ be the PF metric value that user j has on RB q at TS t , where $R^j(t)$ is the total rate achieved

Table 3.3: *Modulation Table*

SINR /dB	Bits/symbol
-6	0.1655
-5	0.2056
-3	0.3142
-1	0.4722
1	0.6935
3	0.99
5	1.3676
8	2.0789
9	2.3497
11	2.9315
12	3.2389
14	3.8789
16	4.5437
18	5.2251
20	5.9174

by the user so far. This means that each RB is assigned using the following equation:

$$\max \sum_i \sum_c x_q^j(t) \lambda_q^j(t), \quad (3.11)$$

where $x_q^j(t)$ is 1 if user j can transmit at rate $r_q^j(t)$ at TS t on RB q . To avoid initial allocation conflicts, the order in which RBs are considered within each BS is randomized.

3.4.7 Traffic model

All mobile stations (MSs) have data to transmit at all time slots. This approach eliminates any effects due to transient phases between different loading levels in the system. Moreover, it allows loading levels to be easily established as a function of the number of users deployed in the system and the required data rate distribution.

The proposed schemes in this thesis, EESBS, bandwidth expansion mode (BEM) and time compression mode (TCoM), can be operated in two modes with respect to the benchmark system. They can either try to achieve the same data rates per user as the benchmark has or try to be as close to the initially allocated users' desired rates as possible. The first mode allows for a fair comparison in terms of energy consumption as it is a comparison between two systems that achieve the same user satisfaction in terms of data rate. The second one allows

the true delivered data rate potential of the proposed schemes to be achieved, as there are no restrictions on their performance apart from what the users require.

3.4.8 Power control

A power control algorithm is necessary to ensure that the minimum feasible transmission powers can be calculated, so that the proposed technique can be correctly evaluated. The system employs the Foschini-Miljanic simple power control algorithm described in (3.4). It is important to allow both the proposed technique as well as the benchmark to use power control so that the comparison is fair. Results are obtained in the steady state *i.e.* the transmission power vector is given a sufficient number of power control loop iterations to converge. Convergence is measured by comparing the difference between power vectors between one and the next iteration of the algorithm. A maximum change of 0.1% is chosen to represent the convergence. In the original paper [95], it is shown that such convergence is possible within 10 control loop iterations.

3.5 Simulation Results

The performance of the benchmark and EESBS is simulated using the aforementioned framework. Two sets of results are presented here – with and without rate matching for the EESBS system. The first set of results is further subdivided into one with low overhead of 12.9% and high overhead of 26.9%.

3.5.1 Rate matched results

Making sure that the two systems that are being compared deliver the same data rate to the user population allows for a fair comparison of energy consumption. After all, the target of this work is to increase the energy efficiency with no detriment to the achieved data rates in the system.

The simulated scenario is one with low load – between 5 and 9 users are allocated to each BS with rates between 0.5 and 2 Mbps.

The set of rate matched results is subdivided in two parts in terms of amount of communication overhead in order to highlight if overhead has an effect on the performance of the

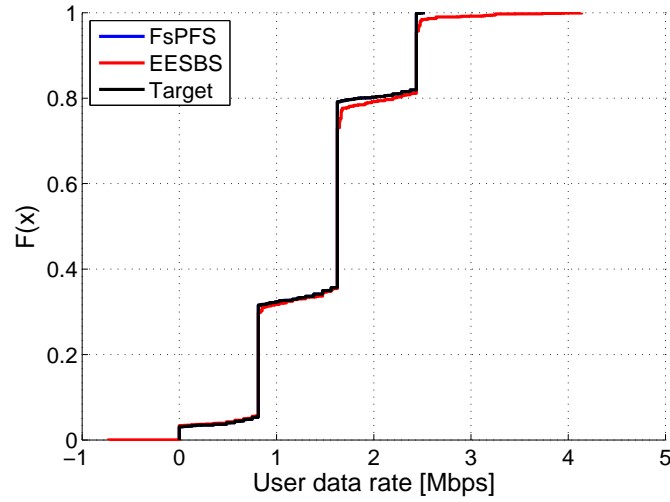


Figure 3.8: User data rate for EESBS with low overhead, $\phi = 0.129$, and load

proposed system. It is important to establish this, since the performance of the techniques introduced later in this thesis actively depends on the amount of overhead present.

3.5.1.1 Low overhead

Fig. 3.8 presents the cumulative distribution function (CDF) of data rate per user. The first thing to notice is that the actual target user rates are different than the ones set up in table 3.1 – $\{0.5, 1, 1.5, 2\}$ Mbps. The difference comes from the fact that the target rates are changed to the ones the FsPF system is able to deliver. Moreover, the difference is also due to limitations in the combinations of modulation modes available, as well as the effect of overhead on the data rate, as the plotted data is corrected for the control overhead.

However, what is important is that EESBS performs slightly better than the desired target, which is set by the performance of the FsPF system. The step-wise behaviour is due to the finite number of quantum data rates assigned to users which can be found in Table 3.1. To reiterate, having the two systems deliver the same data rates to the users allows for a fair comparison in terms of the energy consumption behaviour between them.

The CDF of the energy consumption gain (ECG) performance of the two systems is presented in Fig. 3.9. The first thing that stands out is that the lower the quiescent drain of the BS model, the better the energy efficiency gains are. With the current and realistic target BS models, EESBS achieves an energy saving gain of less than 1% at the 50th percentile. The gains become

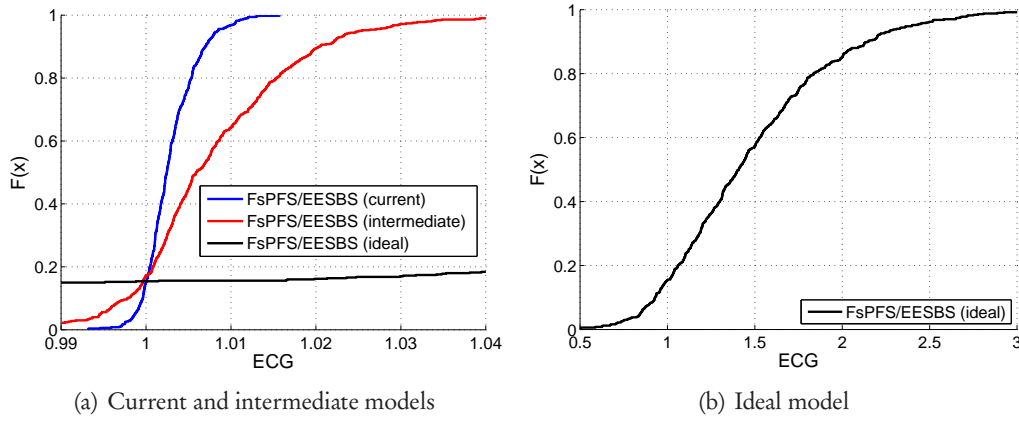


Figure 3.9: *ECG for EESBS with low overhead and load*

significant when the BS energy consumption is governed by the ideal model. Again at the 50th percentile, the proposed system achieves a saving of approximately 29%. It is also important to note that for over 82% of the simulation realizations, the EESBS system achieves an energy saving over the benchmark. In the remaining ones, it achieves a data rate gain. Although the mode of operation is such that the EESBS system should match the data rate achieved by the benchmark, it is possible to achieve slightly higher data rate due to the nature of the allocation algorithm. This is responsible for the remaining 18% of time where the EESBS system does not achieve an energy saving, but rather is able to deliver a better data rate to the users.

The resulting CDF of interference characteristics for the two systems can be found in Fig. 3.10. The EESBS system is able to provide a reduction in the experienced interference in the system by about 0.8 dB at the 50th percentile. This is a result of both the smarter allocation of RBs, as well as the lower RF transmission power overall.

This set of results highlights the need for advancement in BS hardware that will enable EESBS and similar techniques to deliver significant energy reduction gains. However, the reduction in interference levels and radiated RF energy is achieved regardless of the level of energy efficiency in the hardware.

3.5.1.2 High overhead

The simulation results presented in the previous section are repeated for a higher level of overhead, 26.9%, to gauge the effects it has on the system performance. Fig. 3.11 presents the CDF of data rate results. Compared to Fig. 3.8 the achieved rates for the users are lower,

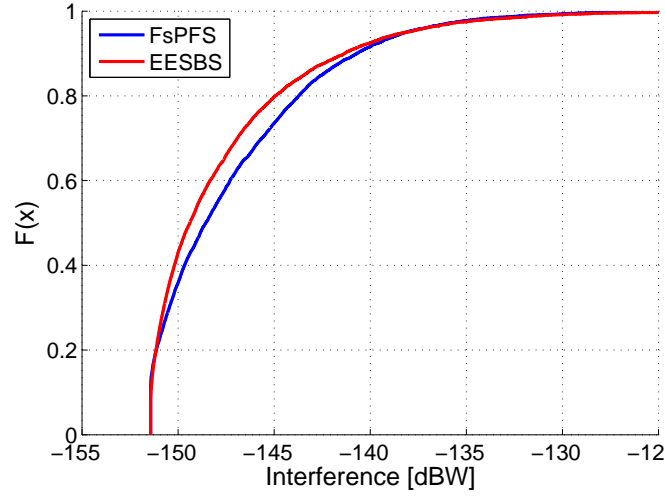


Figure 3.10: *RB interference levels for EESBS with low overhead and load*

which is expected due to the higher overhead in the system. The user data rate targets are retained, hence a higher overhead in the system leads to a lower useful data rate. Otherwise, the behaviour is the same as before.

Following the data rate results, the CDF of ECG is shown in Fig. 3.12. The effect of the increased overhead is to decrease the gain from the hereby proposed scheduler. The percentage of instances when EESBS does not lead to a reduction in energy efficiency increases from approximately 18% to close to 22%. Also, the overall gain decreases, most noticeably in the ECG results for the ideal BS model. The gain at the 50th percentile decreases from 29% to 13.8%. The higher overhead translates in an even smaller dynamic portion of the energy consumption that the scheduler can control. Hence, the possible gain that can be achieved is smaller. In turn, this affects the achieved results by reducing the effectiveness of EESBS.

As expected, there is no change in the interference CDF, since there is no significant change in the actual used RF energy during data transmission.

3.5.2 Rate unmatched results

For the rate unmatched results, a higher level of loading is used in the system. Between 10 and 19 users are distributed per BS. The set of desired user transmission rates is $\{2, 3, 4, 5\}$ Mbps. The overhead is set to 12.9%.

Fig. 3.14 presents the CDF of data rate results. The curve labeled “Target” is the set of allocated

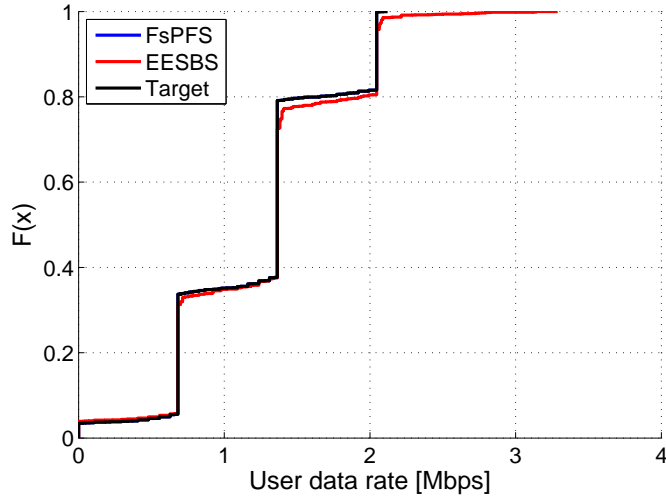


Figure 3.11: User data rate for EESBS with high overhead, $\phi = 0.269$, and low load

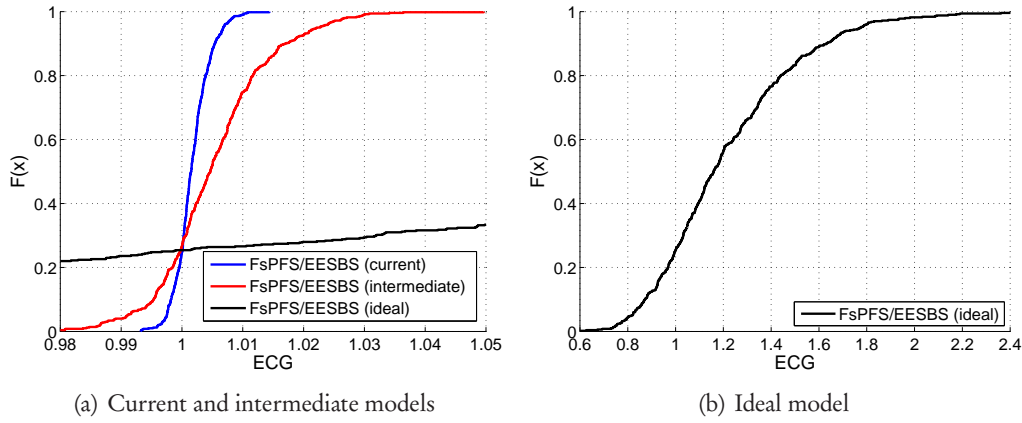


Figure 3.12: ECG for EESBS with high overhead and low load

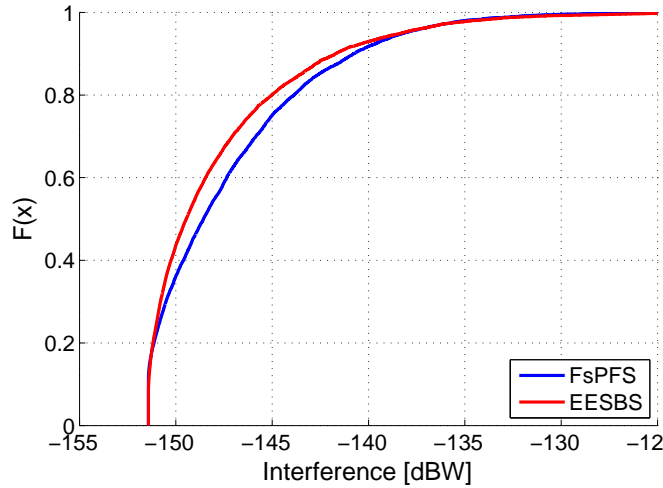


Figure 3.13: RB interference levels for EESBS with high overhead and low load

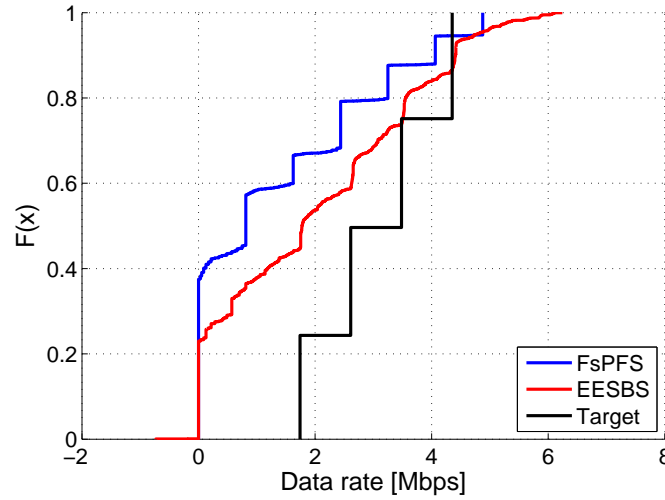


Figure 3.14: User data rate for EESBS with low overhead and high load

to the users desired rates adjusted for overhead. Neither of the two simulated systems is able to achieve the target. However, the EESBS system performs significantly better than its FsPF counterpart. The outage in the smart scheduling system is only 23% compared to 37.5% in the benchmark. Moreover, the data rate achieved at the 50th percentile is 0.81 Mbps for the benchmark, and 1.77 Mbps for the proposed system. The rate is more than doubled.

An important characteristic of any wireless cellular system is the distribution of user data rate with regard to distance from the BS. Fig. 3.15 presents the average data rate per user as a function of distance from the BS. In the first 1/3rd of the cell radius, the average user data rate is higher for the benchmark system by approximately 5%. However, for distances greater than that, the EESBS system outperforms the benchmark. At about 60% of the BS radius, the proposed system is able to serve its users with 1.1 Mbps higher data rate than the FsPF one. At the cell edge the difference is 0.3 Mbps. This is an improvement of 55% and 97% respectively.

However, it is important to see at what expense is the data rate performance increased. The ECG results can be found in Fig. 3.16. It is clear that the EESBS system performs worse than the FsPF one. The loss in overall energy efficiency at the 50th percentile is 2%, 6.4%, and 130% for the current, realistic and ideal BS models respectively. It is important to remember that those losses in energy efficiency are traded for equally large gains in achieved user data rate. In effect, EESBS allows the system to be able to trade off energy efficiency for user data rate, something that the benchmark system is unable to do.

The CDFs of energy consumption rate (ECR) for the two systems with the different BS power

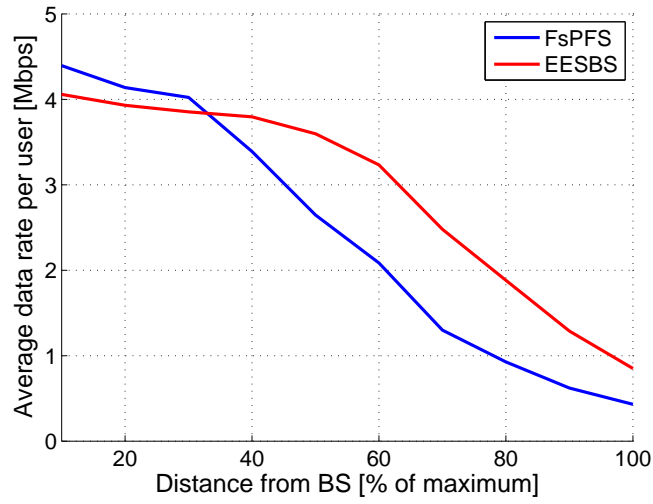


Figure 3.15: Distance vs. data rate for FsPF and EESBS with low overhead and high load

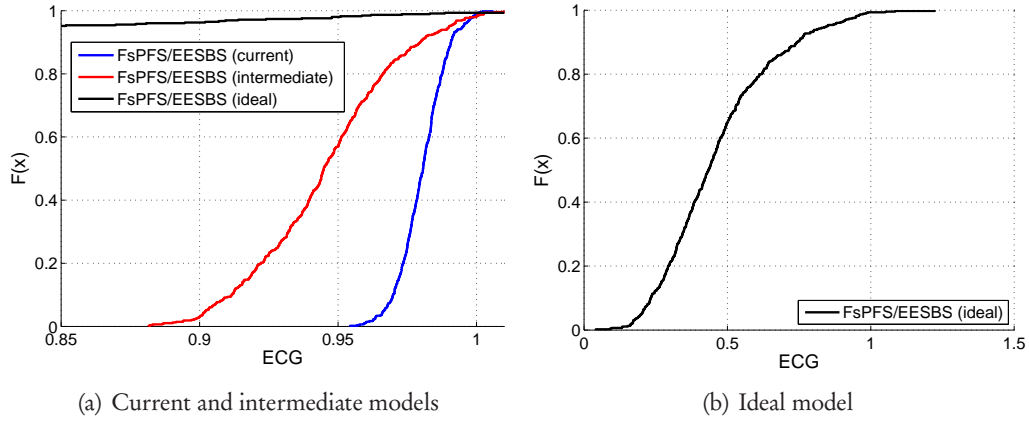


Figure 3.16: ECG for EESBS with low overhead and high load

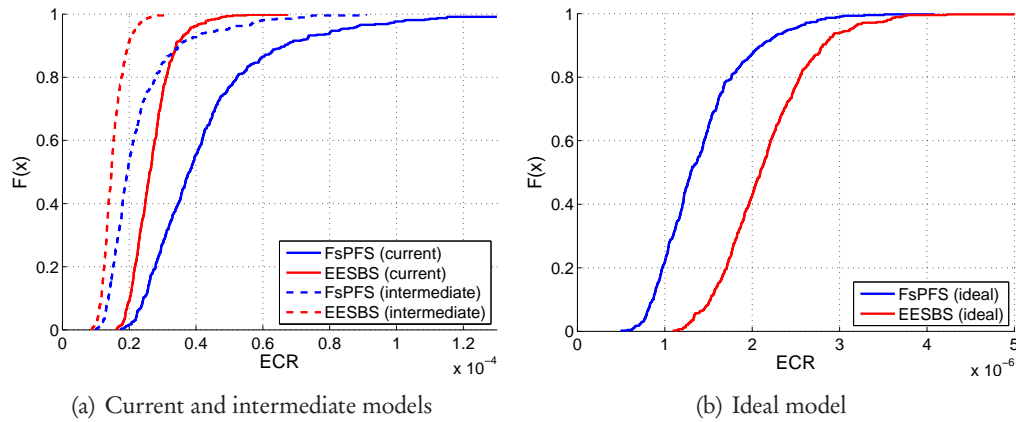


Figure 3.17: ECR for EESBS with low overhead and high load

consumption models can be found in Fig. 3.17. When using the current and intermediate BS hardware energy consumption models, the smart scheduler is able to deliver enough improvement in data rate so that the efficiency with which data is delivered to the end user is better than that of the benchmark system. However, when the ideal BS model is used, the difference in energy consumption between the two systems tips the efficiency in favor of the FsPF system, since the achieved data rates for the users remain the same. For the current and intermediate BS models the improvement in ECR at the 50th percentile is 25% and 32% respectively. For the ideal model, the loss is 38%. However, it has to be pointed out that the operational envelope in terms of achieved user data rate is significantly extended.

The CDF of interference per RB is presented in Fig. 3.18. Due to the higher number of RBs allocated in the EESBS system the overall level of interference is higher. At the 50th percentile the difference between the benchmark and proposed systems is 1.6 dB.

3.5.3 Comparison with results from literature

In order to validate the results obtained from the simulator, studies in the available literature are consulted. The nature of the scenario studied is such that it allows for many parameters to be manipulated, which results in vastly different results. This makes the process of finding comparable studies difficult. Below are presented two studies with similar scenario set-ups the results from which are compared to the results obtained by the simulator described in this work.

Schoenen *et al.* [102] perform a capacity and coverage analysis of a 3GPP-LTE multihop sys-

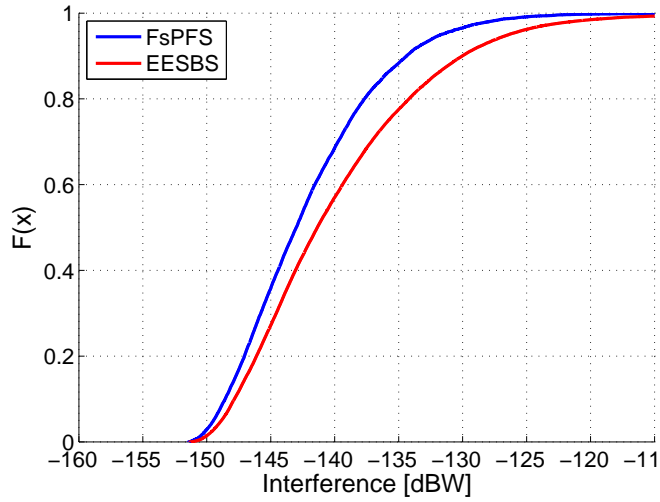


Figure 3.18: RB interference levels for EESBS with low overhead and high load

tem. The scenario used is the city of Jersey with an area of approximately 4.439km^2 . The modulation table used in their work is similar to the one used within this investigation, albeit the fact that the one used here allows for several additional lower speed transmission modes. The used system carrier is 2.5 GHz, which is in contrast with the one used here, 2.14 GHz. Moreover, the transmission power used is 37 dBm compared to the 46 dBm from Table 3.1. Schoenen *et al.* determine that on average when only the BS is used to serve the desired are, a capacity of approximately 16.2 Mbps is achieved along with a coverage of 47%.

Since no CDF plots are presented, the results from the hereby presented simulation results need to be averaged as well. The average number of users in the considered cell within this work is either 7 or 14.5 for the low load and high load scenarios respectively. Next the average data rate per user is to be determined from the CDF results of data rate, after calculation the average is 1.25 and 1.5 Mbps for the two scenarios respectively. This means that the average achieved data rate by the FsPF system varies between 8.75 and 21.75. This means that the results achieved by Schoenen *et al.* are in agreement with the ones presented in this work. The difference can be attributed to the different channel models used as well as the much larger cell area covered in their work.

Zeljko and Simic [103] perform a network layer simulation of the LTE downlink capacity in the wide area of Belgrade city. The existing Wideband CDMA (W-CDMA) network is taken as a starting point for the LTE deployment design. The most notable difference in the simulation setup is the way that users are scheduled. Only one user is scheduled per transmis-

sion time interval per BS. The transmission is done with full power and no power control. Also sectorization is utilized, which inevitably increases the capacity of the network. Regardless of the differences, the results obtained by the authors are between 15 and 25 Mbps for different loading levels. These values are very similar to the ones presented above for the simulator used within this work. The best comparison can be made between the capacity achieved by the high load system presented in this work, 21.75 Mbps, and the results at 100% load presented by Zeljkovic and Simic, 17.24 Mbps. The difference likely stems from the very different scheduling approaches applied.

3.6 Summary

In this chapter, a novel scheduling mechanism is outlined. It is based on the score-based scheduling principle, but targeted at improving energy efficiency without compromising data rate and fairness. A simulation platform to test the performance of the proposed EESBS system against a benchmark FsPF system is described, and used to obtain results.

It is demonstrated that when the EESBS system is tested against the FsPF one, such that it delivers the same user data rate performance, it is able to provide energy efficiency gains. The size of these gains depends on the underlying BS hardware energy consumption model. Small gains are observed for the current and intermediate models. The ideal BS model allows the full potential of the proposed scheduler to be revealed. The best case reduction in used energy is approximately 29% at the 50th percentile. In practice, the gains will heavily depend on the advancement of energy efficiency in hardware. However, it is envisioned that the potential gains will be somewhere in between the results obtained for the intermediate and ideal models.

When the EESBS and FsPF systems are tested in a heavily loaded scenario where it is not expected that the desired user data rates are met, the EESBS system considerably outperforms the benchmark. At the 50th percentile of data rate, the proposed system is able to increase the delivered data rate to the user by more than 100%. The same is true when the user data rate is presented as a function of distance from the BS. The smart scheduler is able to increase the data rate of users who are located at a distance more than one third of the cell radius away from the BS. The data rate of the users at the cell edge is increased by more than 150%. This increase in average user data rate and hence fairness is achieved by allowing a loss in overall used energy compared to the benchmark. In the case of the current and realistic BS models, the

loss is less than 3 and 6% respectively. When the ideal BS hardware model is applied, the loss becomes significant at about 130%. When the energy efficiency is assessed in terms of ECR, the EESBS system is able to deliver data more efficiently in terms of energy per bit than FsPF for the current and intermediate BS hardware models by reducing the energy per bit by 25% and 32% respectively. However, this is reversed for the ideal BS model. It is important to keep this in perspective of the very high gains in user data rate. The proposed EESBS algorithm is able to allow the system to be more energy efficient and achieve higher data rates for the current and intermediate BS models. In the ideal BS case, the loss in efficiency is small enough to be outweighed by the gain in user data rate.

In conclusion, the EESBS system is able to achieve a significant increase in user data rate and reduction in the radiated RF power when used in conjunction with the current and intermediate BS hardware models. This is done with a gain in energy efficiency. When the system is tested in a scenario where the ideal BS hardware model is used, it is able to either deliver an improvement in energy efficiency of approximately 29% at the 50th percentile or more than double the data rate again at the 50th percentile and for distances larger than 60% of the cell radius.

Chapter 4

Energy Efficient Bandwidth Use

A system that is channel, interference and energy consumption aware through a smart scheduler can achieve significant improvements over standard solutions as shown in the previous chapter. However, it might not necessarily be able to make use of all opportunities available to save energy. One such opportunity arises from the non-uniform distribution of traffic during the day as well as over the population of base station (BS) sites. This results in a lot of bandwidth resources available at BS sites that are experiencing low traffic due to user movement or traffic variations. Moreover, depending on the users' data rate requirements and their channel path loss, some users have their energy consumption skewed towards their useful data transmission, and others towards overhead data transmissions. This chapter presents two solutions that make use of these two effects to deliver better energy efficiency.

The rest of this chapter is organized as follows. Section 4.1 introduces the concept of bandwidth expansion mode (BEM) along with theoretical and simulation results on its performance. The complement to BEM, time compression mode (TCoM), alongside with a performance evaluation of its energy saving capabilities is presented in Section 4.2. This is followed by simulation results on the performance of a combined energy efficient score-based scheduler (EESBS), BEM, and TCoM system named bandwidth scheduling (BWS) in Section 4.3. The chapter concludes with Section 4.4.

4.1 Bandwidth Expansion Mode

The first technique presented in this chapter, BEM, makes use of available bandwidth to reduce energy consumption. It is reasonable to assume that lightly loaded Long Term Evolution (LTE) cell sites will have a lot of unoccupied bandwidth. It is hence advantageous to employ techniques/algorithms that trade-off unused bandwidth for energy efficiency.

4.1.1 Technique Description

BEM operates by allowing a user to expand his limited bandwidth by an integer factor of α while preserving the already achieved data rate. The allocated bandwidth is increased while the modulation order and signal-to-noise-plus-interference ratio (SINR) requirement per frequency channel, Γ_q , are decreased to maintain the communication rate. The technique exploits the energy saving opportunity created through the fact that the transmission rate scales logarithmically with the achieved SINR, and hence transmission power, and linearly with the used bandwidth or number of channels according to Shannon's capacity equation:

$$C_q = B_q \log(1 + \Gamma_q), \quad (4.1)$$

where C_q is the transmission capacity of resource block (RB) q in bits per second and B_q is its bandwidth. From the equation, it is evident that capacity scales linearly with bandwidth and logarithmically with transmission power. Hence, an energy saving can be incurred in a communications system without any degradation in service by expanding the communication bandwidth, and scaling down the transmission power. Moreover, robustness of communication is increased as data is transmitted over more channels or RBs in this case.

Consider the following example frequency RB allocation. A user is allocated 4 out of a maximum 10 RBs and transmits on them with relatively high power. This presents the opportunity to allocate an additional 4 RBs, and switch to a lower order modulation scheme if possible. An overall reduction in expended energy can be hence achieved. For example, doubling the used bandwidth, which increases energy consumption by a factor of two, can be offset by going from 16-quadrature amplitude modulation (QAM) to 4-QAM with an energy reduction factor of 3.16. This results in a net reduction in energy use of 1.58. In a more general scenario, a user can expand his bandwidth footprint by a factor of α that is a real number by choosing an appropriate modulation scheme, SINR target, coding scheme and other required link parameters. However, it must be stressed that only an integer number of RBs can be allocated to each user. The integer constraint on α is imposed within this work for simplicity of derivations.

4.1.2 ECG Derivation

In LTE systems, bandwidth is partitioned in quantum blocks, RBs, hence an adapted and expanded version of Shannon's equation (4.1) for such a system would be:

$$C_q = B_q \log_2 \left(1 + \frac{S_q}{N_0 B_q + I_q} \right), \quad (4.2)$$

where S_q is the total received signal power over the bandwidth of the RB, N_0 is the noise power density, and I_q is the total interference power received on RB q . In the context of extending bandwidth, it might seem that the bandwidth terms in the equation need to be scaled. When applying the technique proposed in this thesis, there is no need to scale the $N_0 B_q$ or B_q term since the RB bandwidth is not changed. The user is allocated more RBs, and not randomly sized larger portions of bandwidth.

Ideally, at all times in the system on all used RBs, the achieved SINR is equal to the desired one:

$$B_q \log_2 \left(1 + \frac{S_q}{N_0 B_q + I_q} \right) \geq B_q \log_2 (1 + \Gamma_q). \quad (4.3)$$

If this inequality is satisfied, energy efficiency and correct transmissions are ensured.

The first step in the theoretical gain derivation is to calculate the BEM mode SINR target, Γ_q^{BEM} , from the regular SINR target, Γ_q . This is done through the use of Shannon's capacity equation. Let us assume that we would like to have the same overall transmission rate after more frequency channels are allocated, this yields:

$$\alpha \left(B_q \log_2 (1 + \Gamma_q^{\text{BEM}}) \right) = B_q \log_2 (1 + \Gamma_q). \quad (4.4)$$

The above equation assumes that perfect power control is present in the system, as well as that the channel gains permit the required Γ_q to be achieved. After some manipulations, we arrive at:

$$(1 + \Gamma_q^{\text{BEM}})^\alpha = 1 + \Gamma_q. \quad (4.5)$$

Hence, Γ_q^{BEM} is the solution to (4.5). In the general case this is:

$$\Gamma_q^{\text{BEM}} = \sqrt[\alpha]{1 + \Gamma_q} - 1, \quad (4.6)$$

since all quantities are strictly positive. The next important step is to calculate what the gain per frequency resource block in instantaneous transmission power is. Let's substitute A_q for $(N_0 B_q + I_q)/G_{kj}^q$, where G_{kj}^q is the path gain between transmitter k and intended receiver j for RB q . It is then possible to calculate the minimum transmission power for the desired SINR target, Γ_q :

$$P_q = A_q \Gamma_q. \quad (4.7)$$

By substituting (4.6) instead of Γ_q in (4.7), we can obtain the needed minimum transmission power in BEM mode, P_q^{BEM} :

$$P_q^{\text{BEM}} = A_q (\sqrt[3]{1 + \Gamma_q} - 1). \quad (4.8)$$

The reduction in energy due to BEM can then be calculated in the form of energy consumption gain (ECG) as:

$$\text{ECG}_{\text{BEM}}^{\text{RF}} = \frac{E_{\text{ref}}}{E_{\text{new}}} = \frac{\Gamma_q}{\alpha (\sqrt[3]{1 + \Gamma_q} - 1)}, \quad (4.9)$$

where E_{new} is the energy required for operation by the investigated system and E_{ref} the energy for the reference system. The radio frequency (RF) superscript stands for radio frequency, as the expression above takes into account only the radiated RF energy used for data transmission. The expression does not take into account variations in channel conditions between different RBs.

Allocating more resources to users by allowing them to enter BEM means that there will be an additional control channel overhead associated with these which will affect the overall energy use. It is important to model this so that the real-world performance of this technique can be better assessed, as discussed in section 3.4.4.

The ECG expression for BEM needs a significant alteration to account for the effect of a constant power control transmission. The effect of the overhead transmission on the energy consumption is modeled as:

$$E_{\text{used}} = L((1 - \phi)P_{\text{data}} + \phi P_{\text{ref}}), \quad (4.10)$$

where E_{used} is the total used RF energy for transmission, L is the length of transmission in seconds, and P_{data} is the data transmission RF power used. After expanding all terms, the new

ECG expression for transmitter k and intended receiver j becomes:

$$\text{ECG}_{\text{BEM}}^{\text{CC}} = \frac{\sum_{q=1}^m (1-\phi) \frac{\Gamma_q(N_0 B_q + I_q)}{G_q^{kj}} + \phi P_{\text{ref}}}{\sum_{q=1}^m (1-\phi) \frac{(\sqrt[2]{1+\Gamma_q}-1)(N_0 B_q + I_q)}{G_q^{kj}} + \phi P_{\text{ref}}}, \quad (4.11)$$

where m is the total number of RBs allocated. This expression takes into account the different channel conditions experienced on different RBs, through the inclusion of the RB specific channel gains.

Switching the operation of a BS from one output RF power level to a lower one has an effect on the efficiency with which RF power is delivered. It is widely accepted that the farther away from peak RF output a BS is operated, the worse its efficiency is. Hence, in the context of this investigation, it is important to use accurate BS energy consumption models as the ones described in section 3.4.3.

Keeping in mind the operation of BEM, the already calculated ECG can be modified to account for hardware operation at a given RF output as follows:

$$\text{ECG}_{\text{BEM}}^{\text{TOT}} = \frac{P_{\text{BS},\text{in}}(P_{\text{BS},\text{out}})}{P_{\text{BS},\text{in}}\left(\frac{P_{\text{BS},\text{out}}}{\text{ECG}_{\text{BEM}}^{\text{CC}}}\right)}, \quad (4.12)$$

where $P_{\text{BS},\text{in}}(P_{\text{BS},\text{out}})$ and $P_{\text{BS},\text{in}}\left(\frac{P_{\text{BS},\text{out}}}{\text{ECG}_{\text{BEM}}^{\text{CC}}}\right)$ are (3.8) expressed in function notation. It is important to note that all the presented equations for the ECG of BEM have a significant drawback. They do not account for the fact that any increase or decrease in energy consumption is a self reinforcing process due to the effects that transmission power levels have on the interference received by nearby cells. This is a dynamic effect akin to a cocktail party effect, where the more conversations going on in the room, the higher the level of noise in it.

This effect is difficult to model theoretically due to its feedback nature. Not only is the transmission power affected by the interference received, but the interference depends on the location of the user that is experiencing it. Moreover, it is difficult to model when the above effect should be used due to the hidden [104] and exposed [105] node problems. It is possible to have a scenario where the reduction of transmission power to one user, has no effect to a user in a nearby cell, who transmits on the same RB.

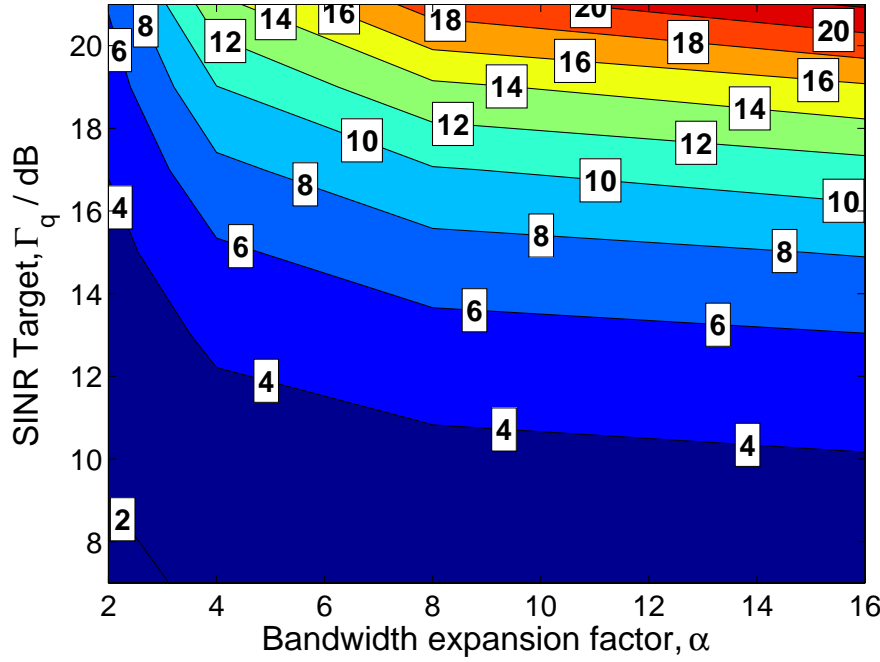


Figure 4.1: *Theoretical RF ECG for BEM*

4.1.3 Theoretical Gains

The expression for the RF ECG can be found plotted in Fig. 4.1. As expected, the energy efficiency gain increases both with higher Γ_q and α . Higher Γ_q means that the initial system uses a less efficient modulation scheme, hence BEM is able to provide higher gains. Higher α means that we are trading more bandwidth for energy efficiency which results in higher overall energy savings. Another trend to observe is that the gain in energy efficiency diminishes with the increase of α for low Γ_q . However, this trend is a lot less pronounced for higher Γ_q . It can hence be concluded, that higher order modulation can benefit from larger factors of bandwidth expansion better than simpler modulation schemes. This also means that it is not possible to infinitely trade bandwidth for energy efficiency and arrive at a broadband system that uses almost no energy.

Equation (4.11) is plotted for an example single carrier system with $\alpha = 2$, $P_{\text{ref}} = 0.4$ W and $\phi = 0.15$ in Fig. 4.2 where RF output power refers to the power radiated from the BS antenna in the system. Control channel overhead introduces new patterns in the gain behaviour for BEM. There is a variation in the gain experienced depending on the ratio between the data and the control channel transmission power. The higher the ratio, the closer to the previously calculated theoretical gains the system performs as the effect of control transmission overhead

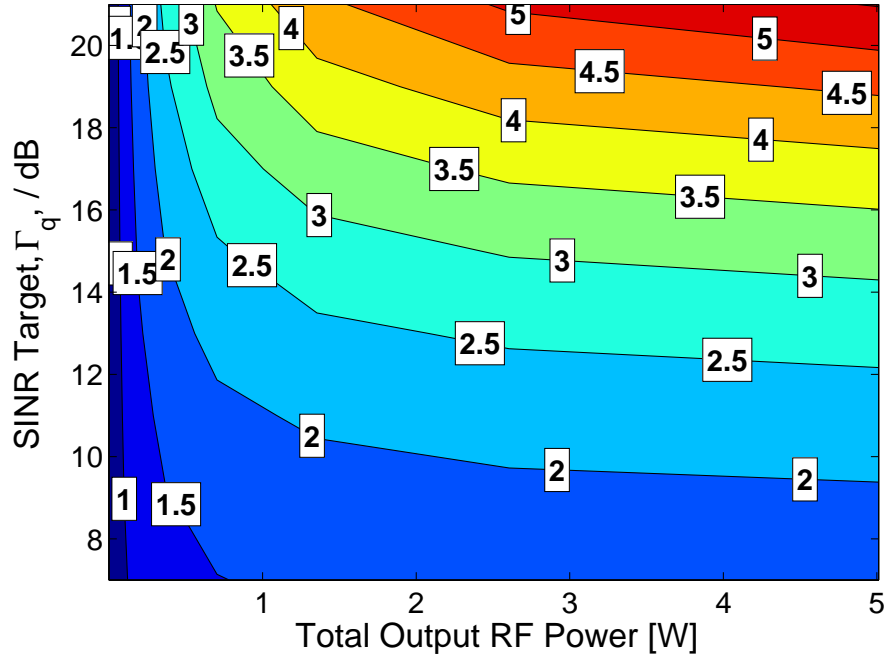


Figure 4.2: *Theoretical ECG for BEM with control channel overhead ($\phi = 0.15$ and $\alpha = 2$)*

becomes negligible. For low values of this ratio, the energy consumption of a communication node is dominated by the control channel overhead. In that case, increasing the number of RBs that are in use compromises the energy efficiency making the use of BEM not desirable. Having a higher initial SINR target before employing BEM results in larger gains from the technique as already established.

A plot of (4.12) for a pre-set ratio of $P_{\text{data}}/P_{\text{ref}} = 3.4$, $\alpha = 2$ and $\phi = 0.25$ can be found in Fig. 4.3. This parameter combination is conservative – low transmission power and high overhead define a scenario where BEM should demonstrate comparatively modest gains. However, even in those conditions the technique provides significant gains. There are two trends to be observed in the figure. First, for a given Γ_q , the gain increases as the total RF output power increases. This is a result of the BS energy consumption model – the energy efficiency of the hardware improves with higher RF power loading levels. This reveals that the BS model has an important role to play in determining the overall gain from BEM. Second, for a given output RF power, the gain increases as Γ_q increases as previously established.

Fig. 4.4 has been realized for a pre-set $\Gamma_q = 11$ dB, $\phi = 0.25$, and $P_{\text{ref}} = 0.4$ W. The parameters are chosen to show that even in high overhead conditions BEM can deliver gains. As the transmission power per RB is increased the gain from BEM increases initially until it converges.

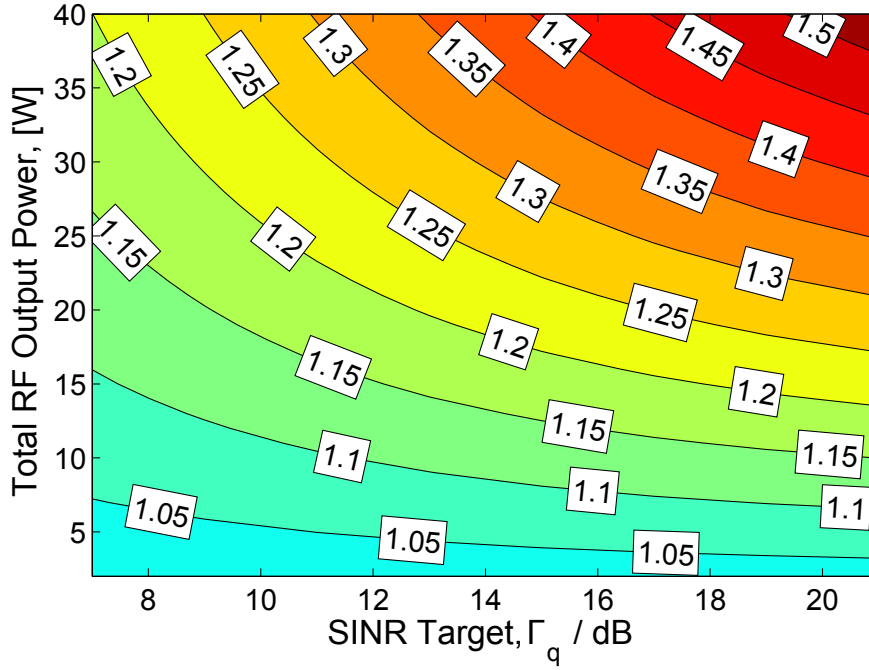


Figure 4.3: Theoretical overall ECG for BEM with fixed data transmission power ($P_{\text{data}}/P_{\text{ref}} = 3.4$, $P_{\text{data}} = 1.53$ W, $\alpha = 2$ and $\phi = 0.25$)

This is due to the shift in ratio between overhead and data energy. A low data-overhead ratio means there will not be any gains from BEM. Conversely, a high data-overhead ratio means there are high gains achievable. After the ratio becomes high enough, the achievable gain is no longer affected by overhead as its contribution becomes insignificant.

4.1.4 Simulation Results

In order for BEM to function correctly, it needs an energy and channel aware scheduler to decide which RBs would benefit from having BEM applied to them. It is possible to use any scheduler which has similar capabilities. However, within this work, the EESBS is used to achieve this functionality since it has good capabilities and enables easy add on of additional techniques on top. The latter is done by simply presenting the scheduler with additional allocation options to evaluate in terms of energy efficiency.

The same simulation scenarios as the ones described in Section 3.5 are revisited for the combined EESBS and BEM system using the simulation platform described in Chapter 3. All the presented results are cumulative distribution functions (CDFs) unless otherwise mentioned.

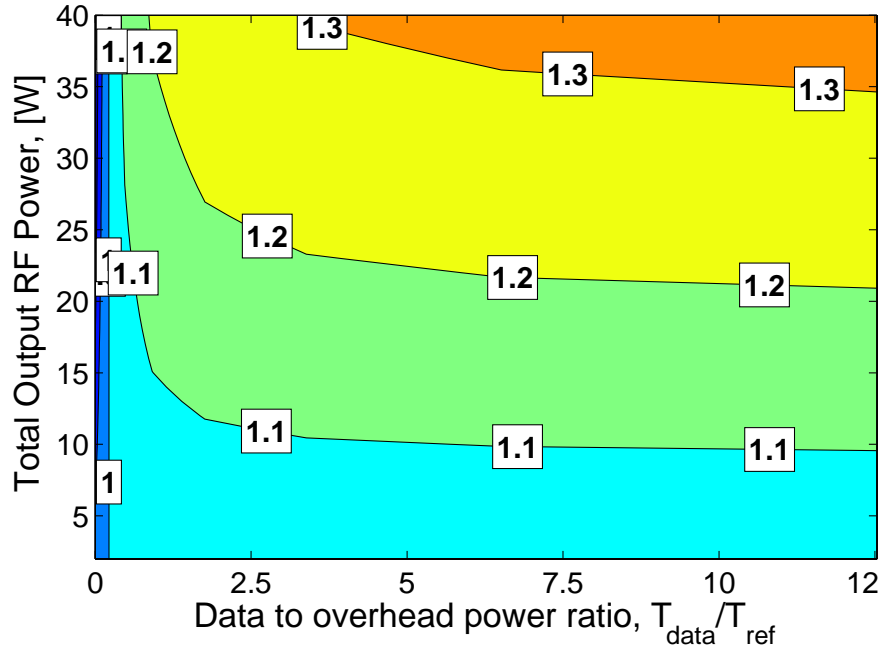


Figure 4.4: Theoretical overall ECG for BEM with fixed $\Gamma_q = 11$ dB ($\alpha = 2$ and $\phi = 0.25$)

4.1.4.1 Rate matched results

Let's once again first consider a scenario with low overhead of $\phi = 0.129$ and low load as described in Table 3.1. The BEM system is forced to deliver the same data rates to the users as the frequency selective proportional fair (FsPF) one. The data rate performance of the two systems can be found in Fig. 4.5. The BEM system is able to slightly outperform the target set by the FsPF scheduler. Comparing these results to the ones for EESBS, BEM does not affect the data rate performance of the system in this scenario.

The equivalent delivered user data rates between the two systems allow for a fair comparison of their respective achieved energy efficiency. The ECG statistics for the two systems are presented in Fig. 4.6. The BEM system is able to provide energy savings in 90%, 95% and 94.4% of cases for the current, intermediate and ideal BS hardware models respectively. At the 50th percentile, the energy savings are 0.3%, 0.9% and 36.6% respectively for the three models used. Once again, it is easy to see that the better the ratio between the quiescent and active energy consumption components in the BS, the better the gains are from the proposed system. It is also important to note that the addition of BEM to the EESBS system has increased the probability of energy reduction from 82% to an average of approximately 92.4%, as well as the energy reduction at the 50th percentile from 29% to 36.6% for the ideal BS hardware model.

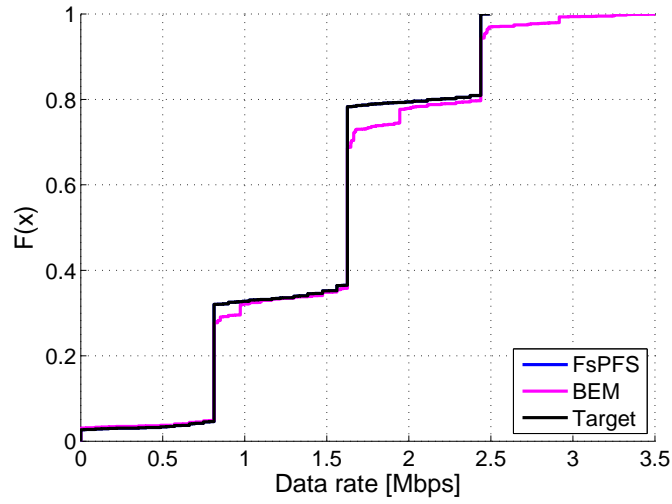


Figure 4.5: User data rate with low overhead, $\phi = 0.129$, and load for BEM

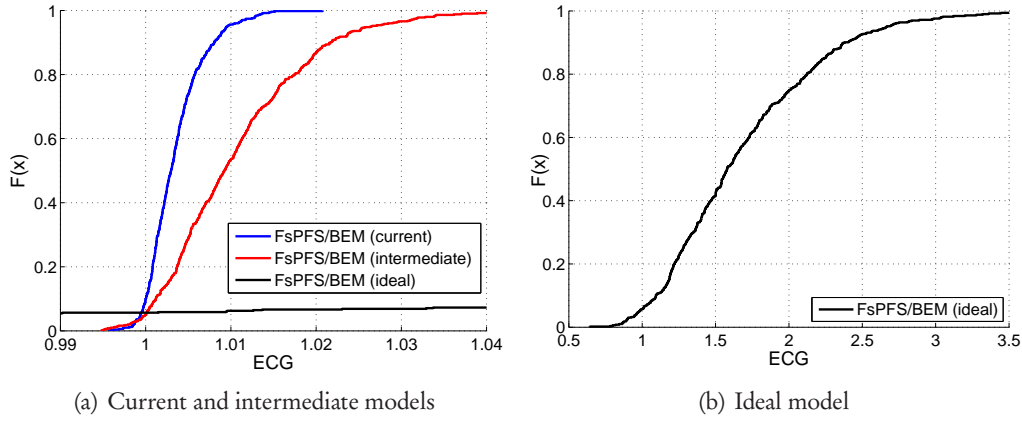


Figure 4.6: ECG with low overhead and load for BEM

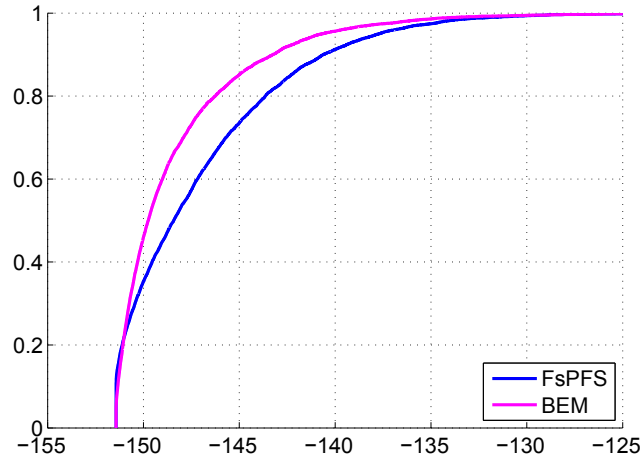


Figure 4.7: RB interference levels with low overhead and load for BEM

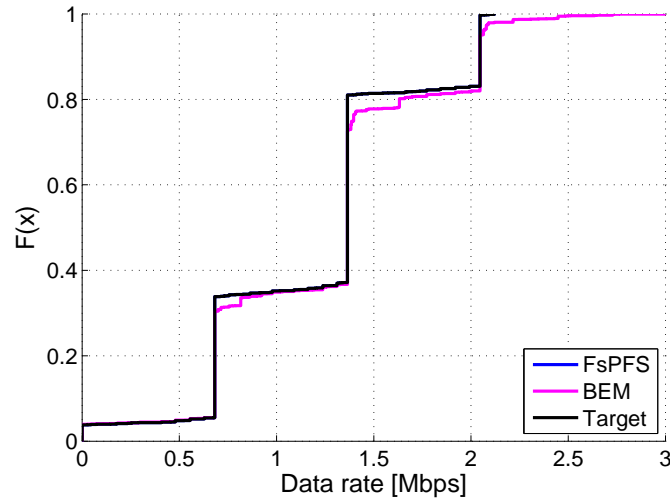


Figure 4.8: User data rate with high overhead and low load for BEM

The RB interference characteristic for the two systems is plotted in Fig. 4.7. The reduction in interference at the 50th percentile due to the combined use of BEM and EESBS is 1.3 dB. This is a further decrease of 0.5 dB compared to the pure EESBS results.

To gauge the effects of overhead on the behaviour of the combined BEM and EESBS system, additional simulations with $\phi = 0.269$ are performed. As Fig. 4.8 illustrates, the achieved user data rates are lower than the ones presented above due to the higher overhead simulated. Again, what is important here is that the two systems being evaluated perform almost identically.

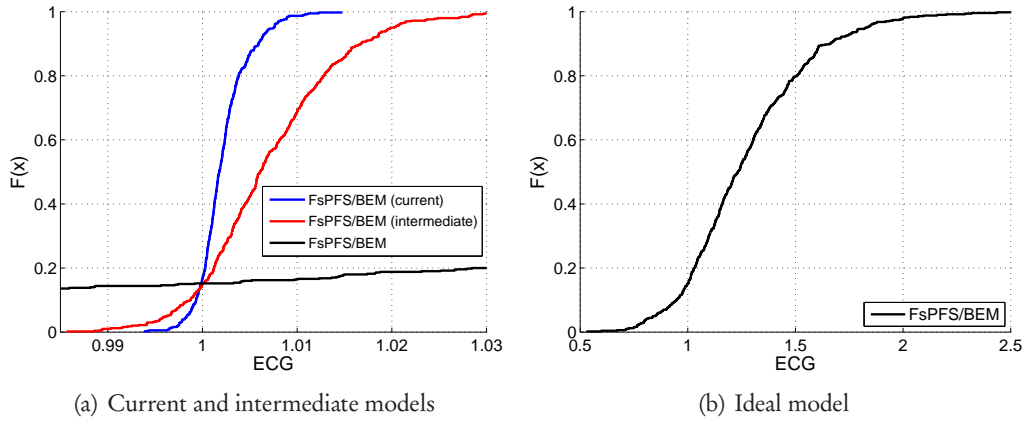


Figure 4.9: *ECG with high overhead and low load for BEM*

The CDF of ECG is the measure of energy efficiency and is presented in Fig. 4.9. Comparing these results with the ones presented above in Fig. 4.6 reveals that there is a significant drop-off in performance due to the additional overhead. The cases in which BEM performs better than the benchmark have reduced by approximately 10% to an average of 85% for the three hardware models. The energy efficiency gain at the 50th percentile remains insignificant for the current and intermediate models. There is a significant reduction in the gain for the BEM system at the same point – it achieves 19.2% energy reduction, down from 36.6% for the low overhead simulation. Comparing these numbers to the results for pure EESBS with high overhead points out that BEM is able to augment the performance of the system despite the overhead. EESBS is able to achieve energy gains in 78% of the simulated cases, and achieves an energy reduction gain of 13.8% at the 50th percentile.

As expected there is not a significant difference in the experienced interference as Fig. 4.10 demonstrates. The difference between the proposed and benchmark systems at the 50th percentile is 1.2 dB.

Comparing the rate matched results for BEM and EESBS reveals that the addition of BEM to the system augments the energy performance without affecting the data rates delivered to the users.

4.1.4.2 Rate un-matched results

Following the rate matched results, here are presented a set of simulation results that are aimed at showing the ability of BEM to improve the achieved data rate, in an energy efficient manner,

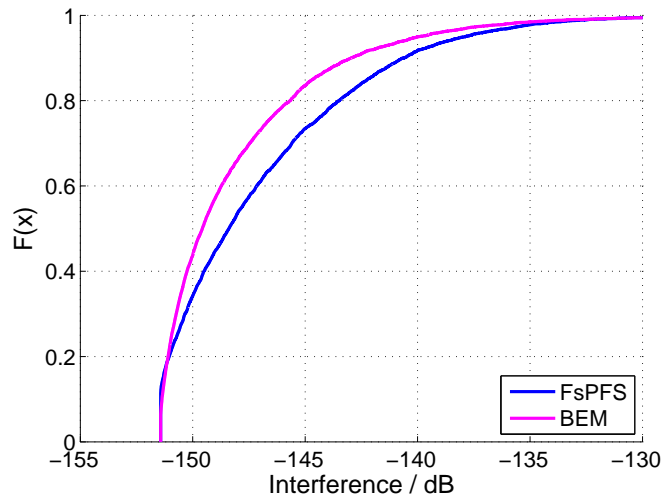


Figure 4.10: RB interference levels with high overhead and low load for BEM

over a benchmark in situations when that is desired *i.e.* periods of high demand.

Fig. 4.11 presents the user data rate results for the BEM system in the high load and low overhead, $\phi = 0.169$, scenario. The FsPF benchmark leaves approximately 39% of the users in outage, whereas the BEM system coupled with the EESBS scheduler is able to reduce that to approximately 25%. This is roughly the same result as the one achieved by the pure EESBS system. The achieved rate at the 50th percentile is 0.81 Mbps and 1.76 Mbps for the benchmark and proposed systems respectively. This is an improvement of 0.95 Mbps or over 100%. Again these results are very similar to the performance shown by EESBS alone. This behaviour is expected as BEM only serves to reduce the energy consumption and not to boost the throughput performance of the system.

User data rate as a function of normalized distance from the BS is plotted in Fig. 4.12. Once again, for the first 30% of the cell radius, the benchmark outperforms the proposed systems by approximately 5%. However, at 60% of the cell radius, the BEM system delivers approximately 1.3 Mbps, or 73%, more than the benchmark. At the cell edge, BEM is able to achieve a rate of 0.67 Mbps versus only 0.35 Mbps from the benchmark, this constitutes an increase of 91%. These results are similar to what EESBS achieves on its own, although slightly lower. The difference in performance is attributed to the different random scenario realizations evaluated. Due to the high computational complexity, and resulting time required, only 100 realizations are simulated per set of results.

The CDFs of ECG can be found in Fig. 4.13. The three different BS hardware models produce

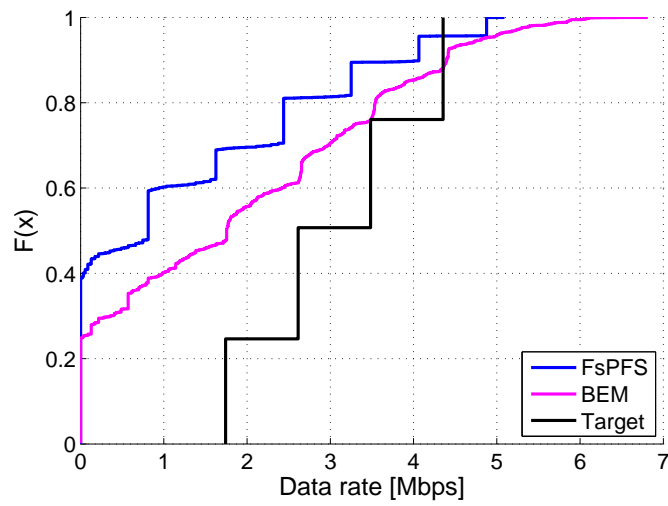


Figure 4.11: User data rate with low overhead and high load for the BEM system

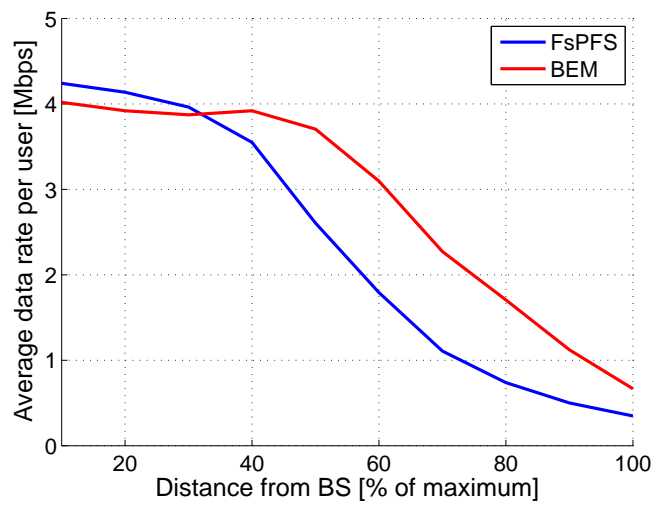


Figure 4.12: Distance vs. data rate for FsPF and BEM with low overhead and high load

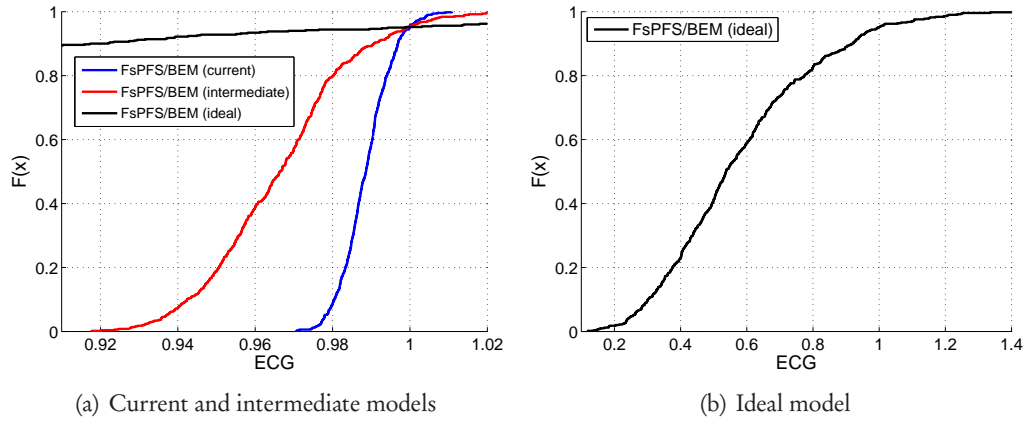


Figure 4.13: *ECG for BEM with low overhead and high load*

very different results. The ECG at the 50th percentile as compared to FsPF for BEM is 0.99, 0.97, and 0.537 for the current, intermediate, and ideal models respectively. These ECG values translate to an increase in energy consumption of 1%, 3%, and 88.7% respectively. Compared to the results for the pure EESBS system there is a noticeable decrease in the loss for the intermediate and ideal models. The EESBS system suffers from 6.4% and 130% loss in those cases respectively. BEM is indeed able to improve the energy efficiency of the system, while retaining the gains in user data rate.

The energy consumption rate (ECR) performance of the combined BEM and EESBS, and benchmark systems is presented in Fig. 4.14. For the current and intermediate models, the BEM system is approximately 32% more energy efficient in delivering data. This performance is comparable with the one achieved by EESBS. However, for the ideal BS model, the BEM system is approximately 22% less efficient than FsPF. This is not a fair comparison due to the significant mismatch in the achieved user data rate by the two systems. Comparing the ECR results for the ideal hardware model with the ones for EESBS, BEM is able to reduce the 61.5% loss in energy efficiency down to only 22%, which is a significant improvement.

The interference per RB is presented in Fig. 4.15. The improvement in energy efficiency is also noticeable in the interference results. The two systems perform very similarly, which is an improvement over the EESBS results, where the proposed scheduler system achieved interference levels worse than the FsPF benchmark.

Overall, the addition of BEM has improved the energy efficiency with little to no detriment to the achievable gains in user data rate. More importantly, there are improvements in energy

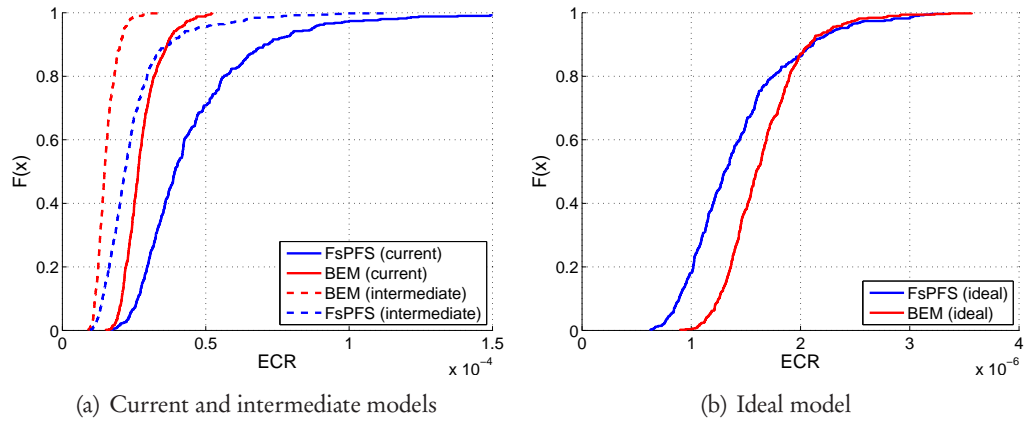


Figure 4.14: ECR with low overhead and high load for BEM

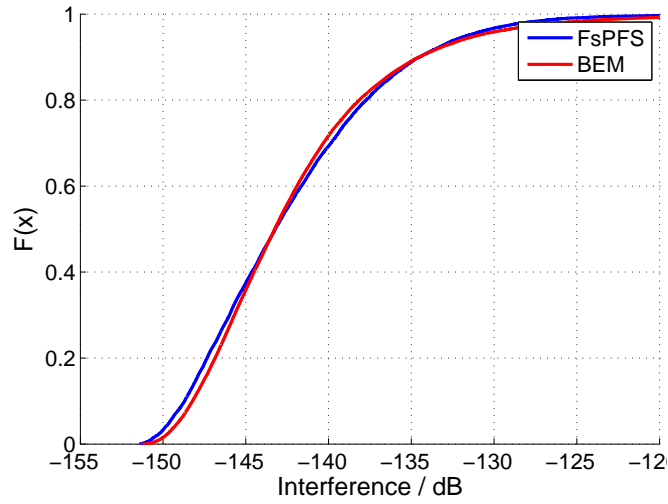


Figure 4.15: RB interference levels with low overhead and high load for BEM

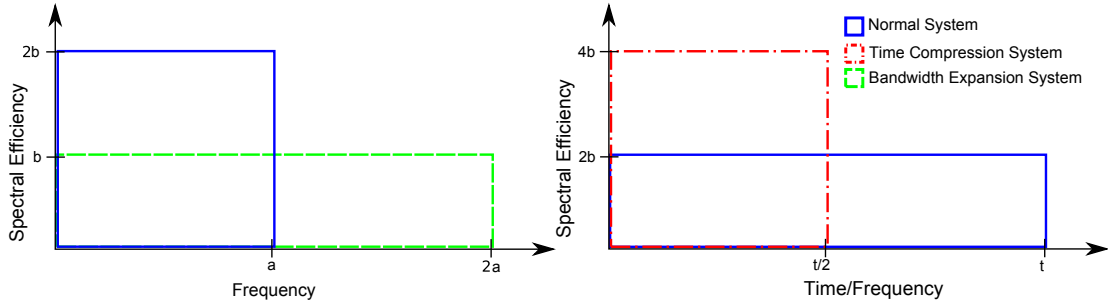


Figure 4.16: System descriptions – left: normal system vs BEM; right: normal system vs. TCoM

efficiency even when improvements in user data rate are made compared to the benchmark system.

4.2 Time Compression Mode

As shown in the previous section, BEM leads to good results when a user's energy consumption is dominated by energy used for data transmission and not control overhead communication. This means a part of the users cannot benefit from the use of BEM. A straightforward way to reduce the energy consumption of these users is to propose a complementary transmission mode. A similar idea has already been described in [68] for a time based implementation. In the prior work, underutilized RBs are lumped together in time without any change in the used modulation. RBs that are then not needed are turned off to conserve energy that would otherwise be wasted in control channel transmissions. In this work, TCoM lumps RBs that are fully utilized on a relatively low modulation order together in time, or alternatively in frequency, and uses a higher order modulation to preserve the data rate. Energy savings are accrued through the reduction in overhead signaling. Naturally, this is done when the channel conditions allow the use of higher order modulation. The following sections will try to establish if the TCoM technique can provide energy saving gains when deployed in realistic scenarios and under what conditions.

4.2.1 Technique Description

A comparison of the three different systems discussed so far can be found in Fig. 4.16, where spectral efficiency is expressed in bits/s/Hz. Decreasing the number of allocated frequency channels in the TCoM system leads to a decrease in the amount of overhead transmissions

required, which suggests that users whose energy expenditure is dominated by control channel transmissions will benefit.

The main difference between the time and frequency based implementations is whether the footprint of the data transmissions are shortened in time or in frequency. By keeping the amount of transmitted data constant, the technique can either shorten the time required for transmission or reduce the bandwidth footprint of said transmission.

To be able to assess the difference between time and frequency implementations of TCoM, knowledge on how energy costs are generated in the system is required. In general:

$$D = \eta L B, \quad (4.13)$$

where D is the delivered payload in bits, η is the spectral efficiency in bits/s/Hz, L is the length of transmission in seconds, and B is the bandwidth in Hz. From this equation it is clear that by increasing the spectral efficiency, it is possible to either decrease the time it takes for a transmission to go through or decrease its bandwidth footprint. On the other hand, the used energy for a transmission can be calculated as:

$$E_{\text{Used}} = P_{\text{data}} L_{\text{data}} m + P_{\text{ref}} L_{\text{ref}} m, \quad (4.14)$$

where E_{Used} is the used total energy, P_{data} is the power dedicated to data transmissions, m is the total number of RBs allocated in the system, and the overall transmission time $L = L_{\text{data}} + L_{\text{ref}}$ is split between user data and reference signaling. The expression assumes equal data transmission powers on all allocated RBs. The same is assumed for the control signal transmission powers as well. The above can be rewritten with the introduction of ϕ :

$$E_{\text{Used}} = m L ((1 - \phi)P_{\text{data}} + \phi P_{\text{ref}}). \quad (4.15)$$

From the above, it emerges that a linear compression or expansion in either bandwidth or time of a transmission, while retaining the overall delivered payload, leads to the same change in used energy. For example, reducing the bandwidth by a factor of two, will yield the same result as taking half as long to complete the transmission if we were to retain the size of the delivered payload and the used modulation scheme. In either the case of reducing bandwidth or length of transmission, it should be possible to turn off the control channel transmissions

on the unused RBs. The number of symbols used for a particular transmission of physical downlink control channel (PDCCH) is set by the BS. Explicitly, it is determined by the channel conditions to ensure that the transmission can be reliably decoded [45]. It should be possible to adapt this functionality in LTE, so that it supports the process of eliminating unnecessary overhead to increase energy efficiency.

In this work, the frequency implementation of TCoM is considered as it is in line with the concepts used in BEM and makes for a good complement technique to it.

4.2.2 ECG Derivation

As outlined above, time and frequency implementations of TCoM should not differ in performance, hence only the frequency based system derivation of the gains is presented. To make sure that the two systems deliver the same amount of data, the following needs to be satisfied:

$$R_{\text{TCoM}} = R_{\text{benchmark}} \beta, \quad (4.16)$$

where the subscripts denote the different systems, R is the transmission rate, and β is the time/bandwidth compression factor, which is an integer similar to α . From (4.16) and Shannon's capacity equation, we can derive the required SINR target for the TCoM system:

$$\Gamma_q^{\text{TCoM}} = (1 + \Gamma_q)^\beta - 1, \quad (4.17)$$

where Γ_q^{TCoM} is the TCoM SINR target. From the basic SINR calculation formula, the required RF power can be calculated:

$$P_q^{\text{TCoM}} = \frac{N_0 B_q + I_q}{G_q^{kj}} \Gamma_q^{\text{TCoM}}. \quad (4.18)$$

The total expended RF energy to deliver a payload on β RBs in the benchmark system and the same payload in the proposed system can be calculated as:

$$E_{\text{benchmark}} = L \sum_{q=1}^{\beta} ((1 - \phi) P_q + \phi P_{\text{ref}}) \quad (4.19)$$

$$E_{\text{TCoM}} = L ((1 - \phi) P_q^{\text{TCoM}} + \phi P_{\text{ref}}). \quad (4.20)$$

The RF ECG can now be calculated from basic principles and (4.18) with the assumption that all P_q and P_q^{TCoM} are the same between RBs respectively as:

$$\text{ECG}_{\text{TCoM}}^{\text{RF}} = \frac{\beta \Gamma_q}{(1 + \Gamma_q)^\beta - 1}, \quad (4.21)$$

where the assumption is that all used RBs are experiencing nearly identical channel conditions, which is generally not true in practice. If the control channel transmissions are to be accounted for as before as well as different channel conditions, the above becomes:

$$\text{ECG}_{\text{TCoM}}^{\text{CC}} = \frac{\sum_{q=1}^{\beta n} (1 - \phi) \frac{\Gamma_q (N_o B_q + I_q)}{G_q^{\text{kj}}} + \phi P_{\text{ref}}}{\sum_{q=1}^n (1 - \phi) \frac{((1 + \Gamma_q)^\beta - 1) (N_o B_q + I_q)}{G_q^{\text{kj}}} + \phi P_{\text{ref}}}. \quad (4.22)$$

Following the manner of the BEM ECG derivation, (4.22) is modified to account for hardware efficiency:

$$\text{ECG}_{\text{TCoM}}^{\text{TOT}} = \frac{P_{\text{BS},\text{in}}(P_{\text{BS},\text{out}})}{P_{\text{BS},\text{in}} \left(\frac{P_{\text{BS},\text{out}}}{\text{ECG}_{\text{TCoM}}^{\text{CC}}} \right)}. \quad (4.23)$$

4.2.3 Theoretical Gains

The ECG for RF energy for TCoM is plotted in Fig. 4.17. Again, as indicated by the form of (4.21), higher Γ_q and β mean lower energy efficiency gains. Since, there is no region on the graph where the gain is greater than 1, the technique does not grant any gains when overhead is not considered. This is to be expected, since TCoM saves energy by reducing overhead consumption.

Equation (4.22) is plotted in Fig. 4.18 for $\phi = 0.25$, $P_{\text{ref}} = 0.4$ W, and $\beta = 2$ to underline the gains from TCoM. The gain from TCoM decreases as P_{data} increases, which means that TCoM is most beneficial to users with high $P_{\text{ref}}/P_{\text{data}}$ ratio. Also, the gain decreases with increase in Γ_i . This confirms that the users most likely to benefit from TCoM are ones that enjoy very good channel conditions while not requiring high data throughput *i.e.* their energy consumption is dominated by control channel transmissions. Such users are most likely to be found in the cell center.

Fig. 4.19 presents (4.23) plotted for a ratio of data to overhead transmission power, $P_{\text{data}}/P_{\text{ref}}$,

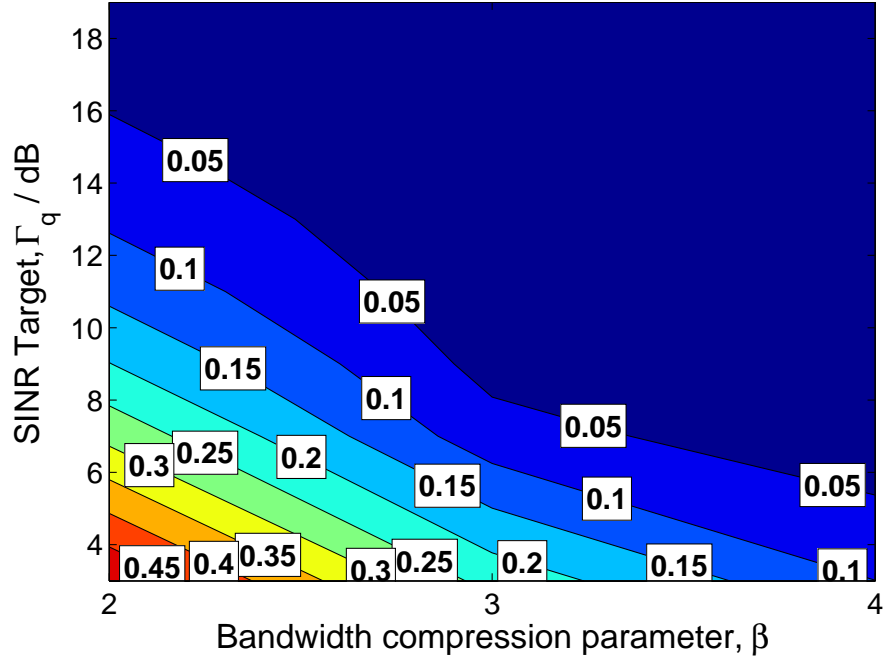


Figure 4.17: *Theoretical RF ECG for TCoM*

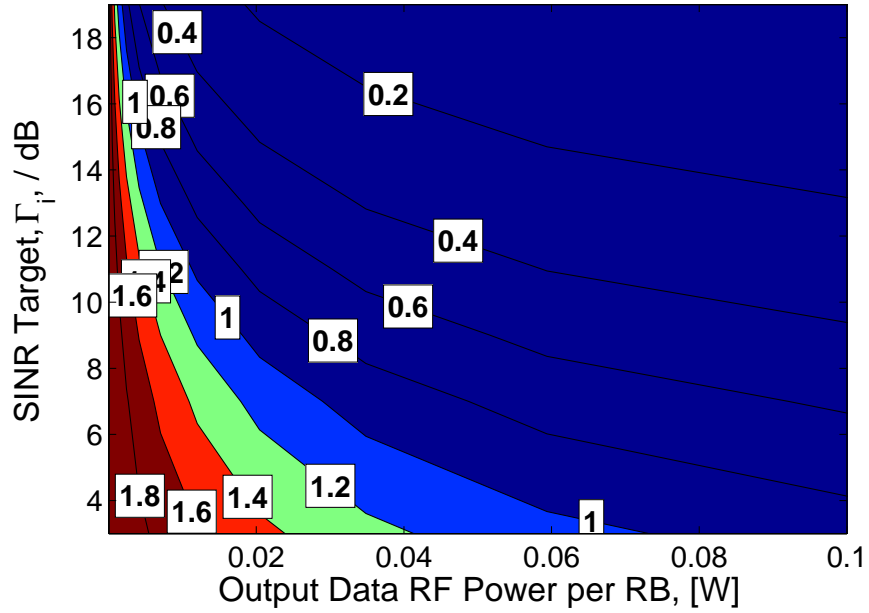


Figure 4.18: *Theoretical ECG for TCoM with control channel overhead ($\phi = 0.25$ and $\beta = 2$)*

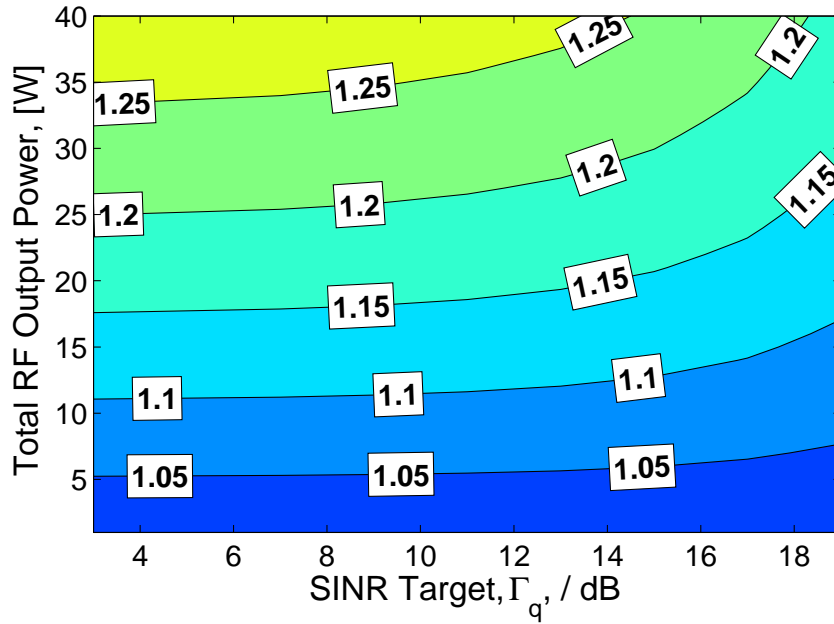


Figure 4.19: Theoretical overall ECG for TCoM with $\phi = 0.25$, $\beta = 2$, and $P_{\text{data}}/P_{\text{ref}} = 0.0012$

of 0.0012. This value is reasonable and conservative considering the path loss difference experienced by a user in the cell center and one on the cell edge. A ratio of 0.0012 represents a distance of about 20 meters in terms of pathloss. Two trends can be observed. First, the higher the total output RF power, the higher the gain from TCoM. This is due to the fact that the higher the initial loading the more efficient the operation of the system after the required total output power has been reduced through TCoM. Second, the higher the initial SINR target, the lower the gain from TCoM for a given total RF output level. This is due to the fact that more complex modulation techniques are less energy efficient than the simpler ones.

The theoretical results lead to the conclusion that users with low data rate requirements that enjoy good channel conditions and have relatively high amount of RBs allocated to them are going to achieve the highest energy savings due to TCoM.

4.2.4 Simulation Results

Similar to BEM, TCoM also requires an energy and channel aware scheduler to function properly. As with BEM, EESBS is used to achieve this functionality within the simulation framework.

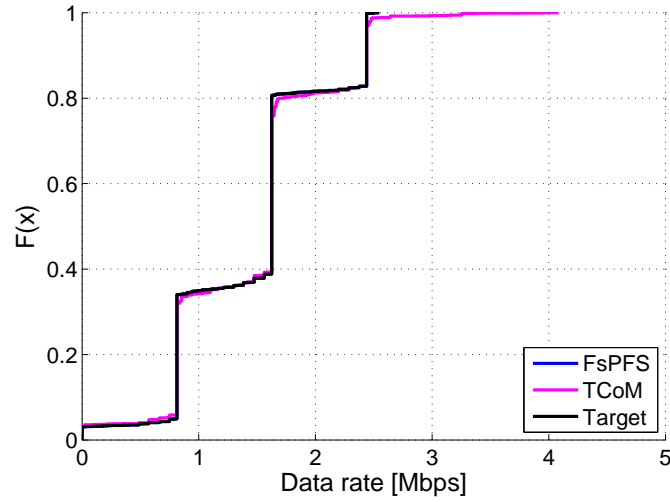


Figure 4.20: User data rate with low overhead, $\phi = 0.129$, and load for TCoM

The same simulation scenarios as the ones described in Section 3.5 are revisited for the combined EESBS and TCoM system using the simulation platform described in Chapter 3. All the presented results are CDFs unless otherwise mentioned.

4.2.4.1 Rate matched results

For the comparison of the energy efficiency performance of the TCoM system against the benchmark FsPF one, the proposed system is forced to match the achieved user data rates by the benchmark. This puts the two systems on equal footing in terms of delivered user data rate, so that the energy consumption comparison is fair.

Starting with the low overhead and low load scenario, the data rate performance of the two systems can be found in Fig. 4.20. The proposed system slightly outperforms the FsPF benchmark, but remains extremely close to its performance.

The CDFs of ECG for the proposed TCoM and benchmark systems are presented in Fig. 4.21. The TCoM system performs better than the benchmark in 84%, 89% and 88% of the time for the current, intermediate and ideal BS hardware energy efficiency models respectively. At the 50th percentile the energy efficiency gain is 0.3%, 0.8% and 28.9% for the different models respectively. The performance is slightly worse than that of BEM with regard to the percentage of time when a reduction in used energy is provided. When compared to pure EESBS, there is an improvement of 2% – 7%. In terms of the gain at the 50th percentile,

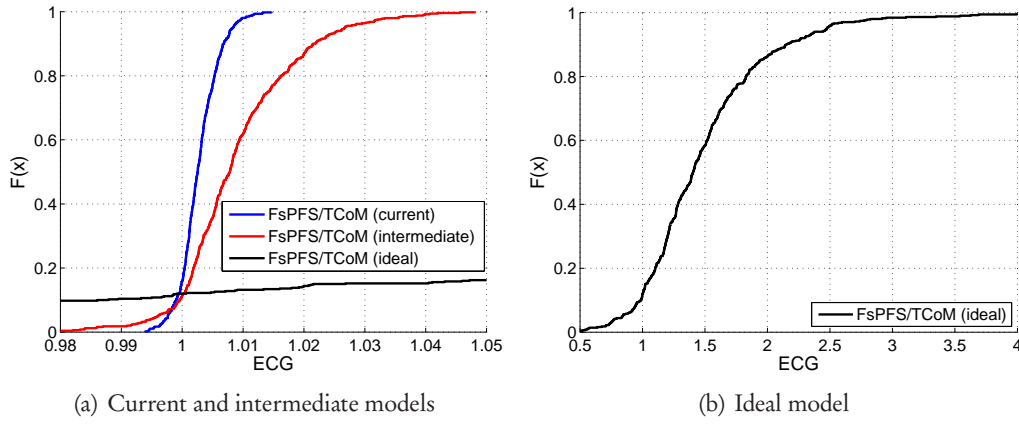


Figure 4.21: ECG with low overhead and load for TCoM

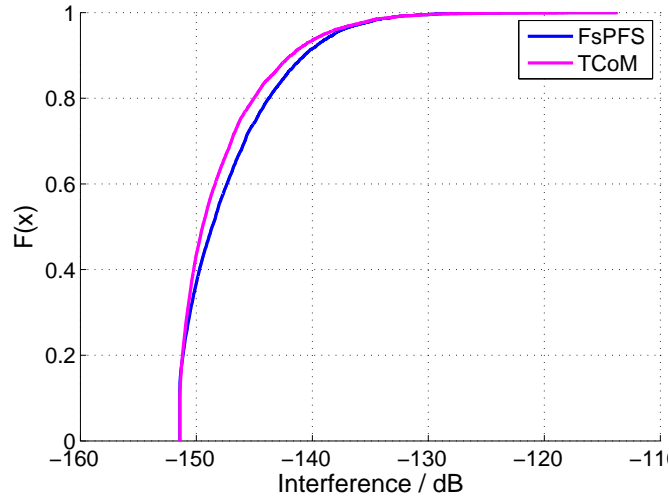


Figure 4.22: RB interference levels with low overhead and load for TCoM

TCoM performs approximately the same as EESBS. The TCoM system does not provide substantial gain over EESBS due to the low level of overhead in the system.

Fig. 4.22 presents the CDF of interference received on a RB basis. The difference between TCoM and the benchmark at the 50th percentile is 0.9 dB which is comparable to the performance of EESBS.

In order to have an appreciation for the effects of overhead on the system performance, the low overhead results need to be compared to the ones with high overhead, $\phi = 0.269$. The user data rate adjusted for overhead can be found in Fig. 4.23. The performance is qualitatively the same as in the low overhead scenario. As expected, the achieved data rates are lower due to the additional overhead.

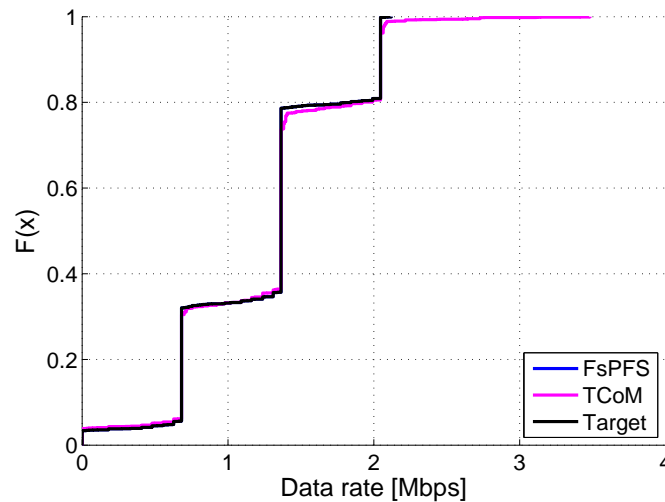


Figure 4.23: User data rate with high overhead and low load for TCoM

The ECG performance of the proposed system compared to the benchmark is plotted in Fig. 4.24. The percentage of the time when TCoM is able to provide energy savings remains approximately the same as compared to the low overhead results. Compared to EESBS, this is an improvement by 5%. BEM is able to perform marginally better by improving over EESBS by 7%. In terms of the gain at the 50th percentile, the TCoM system achieves a saving of 0.2%, 0.6% and 16.7% for the current, intermediate, and ideal hardware models respectively. This is an increase of 3% over the pure EESBS system, and a reduction of 2.5% over the BEM system. A relativistic comparison reveals that the performance gap between BEM and TCoM is smaller for the high overhead scenario.

The lack of appropriate candidate users due to the user distribution has a strong effect the performance of TCoM. Candidate users are ones who are close to the BS, enjoying a high channel gain, and with a low data rate requirement. Since the users are uniformly distributed in the cell area, that means that there are more users at a larger distance from the BS rather than close to it. This favors BEM as it delivers energy savings by targeting the cell edge users.

Lastly, the interference performance of the two evaluated systems is presented in Fig. 4.25. The difference between the FsPF and proposed system is 1 dB at the 50th percentile. This is higher by 0.2 dB than the decrease in interference achieved by EESBS alone, and 0.3 dB lower than what BEM is capable of in the same scenario.

The results presented in this section do not establish TCoM as a technique that can deliver high gains on its own. The scenario conditions in which it is able to reduce the energy con-

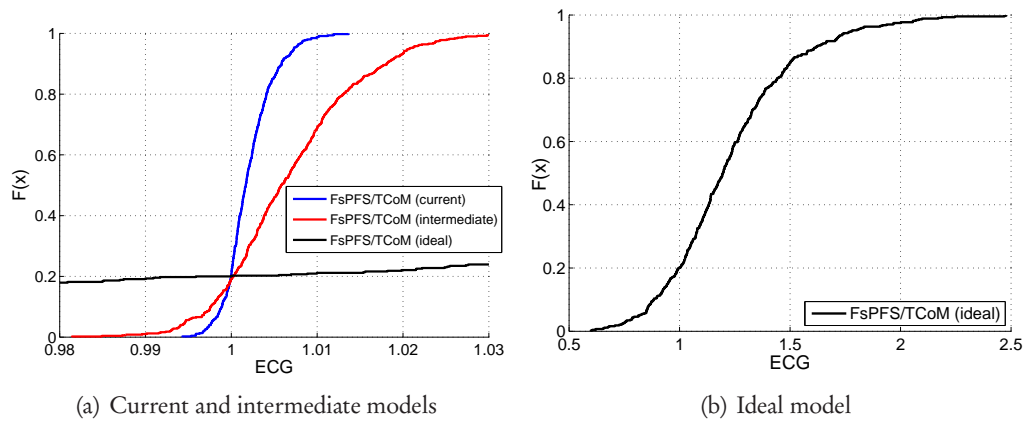


Figure 4.24: ECG with high overhead and low load for TCoM

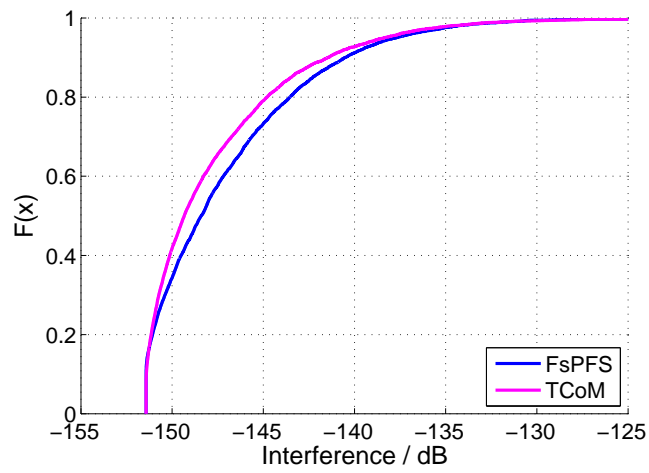


Figure 4.25: RB interference levels with high overhead and low load for TCoM

sumption significantly are highly specific and require a population of users with good channel conditions, very low data rate requirements and a significant number of RBs allocated to them. These results are in line with the theoretical predictions. However, another strength of TCoM is its ability to shift resources used in the center of the cell towards users who are on the cell edge thus creating more opportunities for energy savings by the use of BEM. The benefits of using TCoM should become more apparent within the context of the combined, BWS, system results in Section 4.3, as well as the following rate un-matched results.

4.2.4.2 Rate un-matched results

To gauge the full capabilities of the combined EESBS and TCoM system to deliver data rate improvements to the users, the rate un-matched mode of the simulation platform is used. The results can be found below for the already discussed high load and low overhead, $\phi = 0.129$, scenario.

The achieved data rate performance for the two systems and the user required target is plotted in Fig. 4.26. In terms of outage, the proposed system is able to place only 25.6% of users in outage, compared to 37.5% for the benchmark. At the 50th percentile, the data rate is improved by approximately 1 Mbps over the FsPF system – from 0.8 to 1.76 Mbps, or an improvement of 125%. Compared to the EESBS system, the outage achieved by TCoM is 2.6% higher. The data rate at the 50th percentile is approximately the same. The switch from BEM to TCoM has made almost no difference to the user data rate results as expected. Both BEM and TCoM are designed to not directly affect the data rate.

A plot of average data rate per user as a function of distance is presented in Fig. 4.27. At distances of less than 35% of cell radius, the behaviour of the two evaluated systems is similar to the one shown before. TCoM delivers a slightly lower data rate on average by about 5%. A divergence in behaviour is observed for distances larger than 35% of the cell radius. The proposed system consistently outperforms the benchmark. At 60% of radius, the gain in user data rate is 1 Mbps or 50%, and at the cell edge it is 0.4 Mbps or 99%. Compared to the EESBS and BEM systems, these gains are very similar, and any difference is likely down to the different random realizations of the user populations that have been evaluated.

Fig. 4.28 presents the ECG performance of TCoM compared to the FsPF system. For the current and intermediate BS hardware energy consumption models, TCoM is able to provide

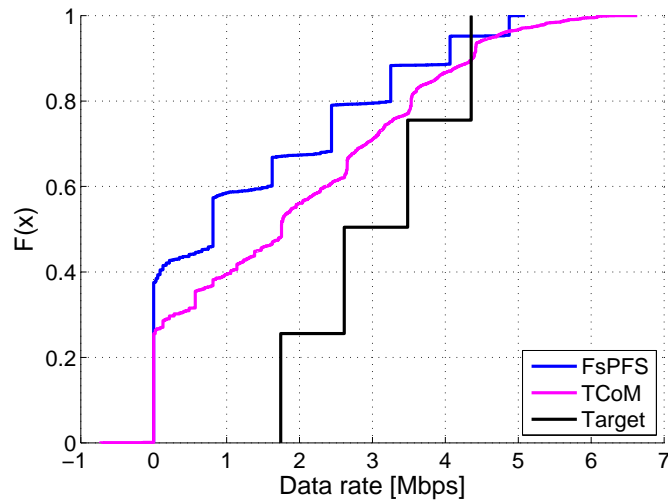


Figure 4.26: User data rate with low overhead, $\phi = 0.129$, and high load for TCoM

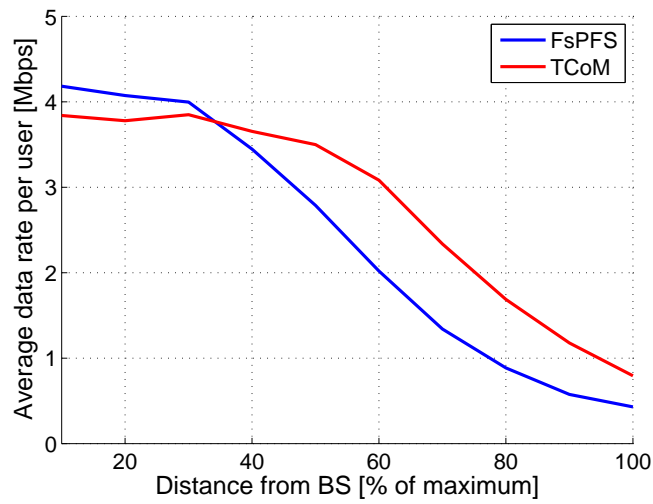


Figure 4.27: Distance vs. data rate for FsPF and TCoM with low overhead and high load

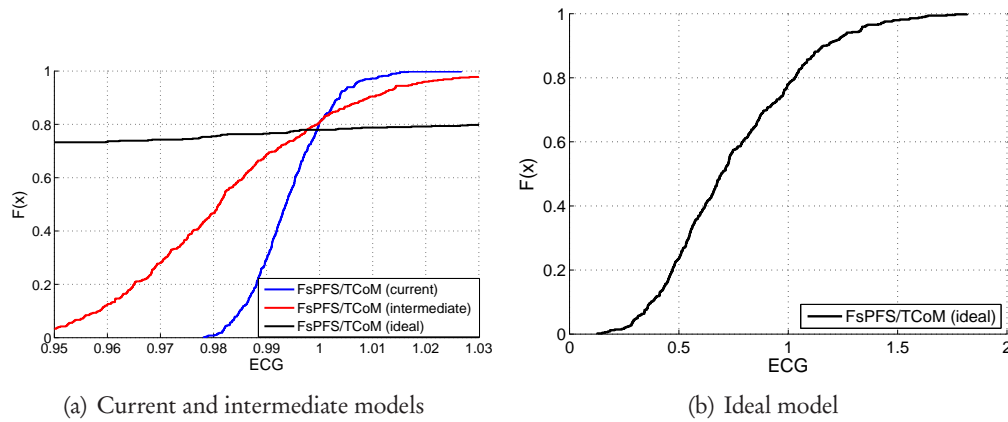


Figure 4.28: *ECG for TCoM with low overhead and high load*

energy savings for 20% of the random simulation realizations. For the ideal BS model, the number is slightly higher at 22%. At the 50th percentile, the loss in energy consumption is 0.6%, 1.9% and 42.5% for the three hardware models. This is substantially better than the values achieved for pure EESBS. Particularly the loss for the ideal BS energy consumption model is 87% less. Compared to BEM, the percentage of time when TCoM is able to provide energy savings is about twice as high. The loss of energy efficiency at the 50th percentile is also less for the TCoM system, most noticeably for the ideal BS model.

The ECR performance for the three different BS energy consumption models can be found in Fig. 4.29. Straightaway, it is easy to notice that compared to the pure EESBS results, the TCoM system is able to perform better under the ideal BS consumption model. It is able to deliver data with better efficiency than the benchmark in approximately 50% of the time. In terms of required energy per bit, the TCoM, BEM, and EESBS systems perform almost identically for the current and intermediate consumption models. This is due to the fact that those models allow for a relatively small part of the consumption to be manipulated by the proposed algorithms, hence the impact of any improvement in those is minimal. However, for the ideal model, the TCoM system performs 35% better than pure EESBS at the 50th percentile. Compared to BEM, the performance is 16% better.

The interference CDF on a per RB basis can be found in Fig. 4.30. At the 50th percentile, the difference between the two systems is 1.3 dB in favor of the TCoM one. Intuitively, this should mean that the energy consumption performance of TCoM should be better. However, TCoM has a lot more RBs allocated, which results in a higher energy consumption. The lower interference levels together with the better overall resource allocation are responsible for the

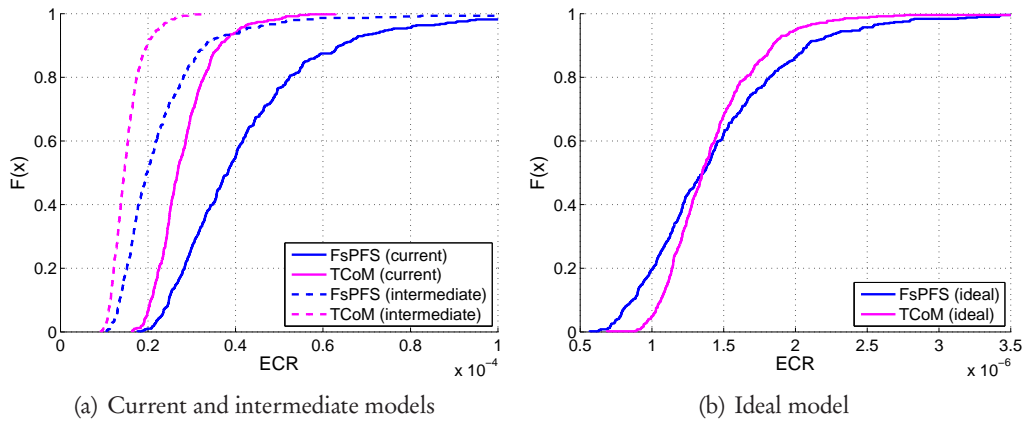


Figure 4.29: ECR with low overhead and high load for TCoM

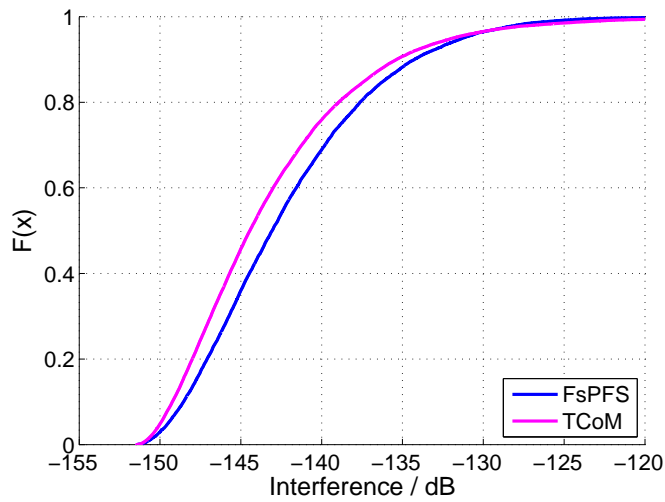


Figure 4.30: RB interference levels with low overhead and high load for TCoM

gain in user data rate. Overall, the interference performance of TCoM is noticeably better than EESBS, by approximately 3 dB, and 1.3 dB better than BEM.

For the high load scenario, the combined TCoM and EESBS system is able to retain the user data rate gains provided by EESBS, but suffer lower losses in energy consumption than both EESBS and BEM. In general, the losses in energy efficiency are lower than the respective gain in user data rate.

4.3 Combined EESBS, BEM, and TCoM Simulation Results

All of the techniques proposed so far reside in the software layer of a potential cellular network. Hence, their implementation comes at a relatively low cost. It is at no additional detriment if all of the proposed systems are integrated. This section presents simulation results for the performance of the combined EESBS, BEM and TCoM system against the FsPF benchmark. This systems is henceforth referred to as BWS or combined system. The simulation scenarios used are the ones already applied in the previous sections.

4.3.1 Rate matched results

The first set of results to be considered is the rate matched simulations for low and high overhead. These results allow for a fair comparison between the proposed and benchmark system in terms of energy efficiency since the delivered user data rate is approximately the same. Also, the effect of overhead can be gauged by the differences in performance between the high and low overhead results.

4.3.1.1 Low overhead

The data rate results for the low overhead scenario can be found in Fig. 4.31. The results follow the pattern established previously as the the two systems behave almost identically. However, approximately 16% of the users in the combined system enjoy a slightly higher data rate than in the benchmark.

Following the user data rate results, Fig. 4.32 presents the CDFs of ECG. The BWS system is able to provide energy savings for approximately 96% of the time across all three BS energy consumption models. At the 50th percentile, the energy consumption reduction due to the combined system is 0.3%, 0.9% and 38.16% for the current, intermediate and ideal models. Compared to the pure EESBS system, the BWS system is able to provide energy savings for 13% more of the time, and the gain at the 50th percentile for the ideal energy consumption model is higher by almost 11%. Compared to the BEM system, the percentage of time which both deliver energy savings is approximately the same. The gain at the 50th percentile is the same for the current and intermediate models, but is 1.5% higher for BWS when using the ideal BS model. Lastly, compared to the TCoM system, the percentage of time that energy consumption reduction is achieved is increased by 9% on average for all three models, the gain

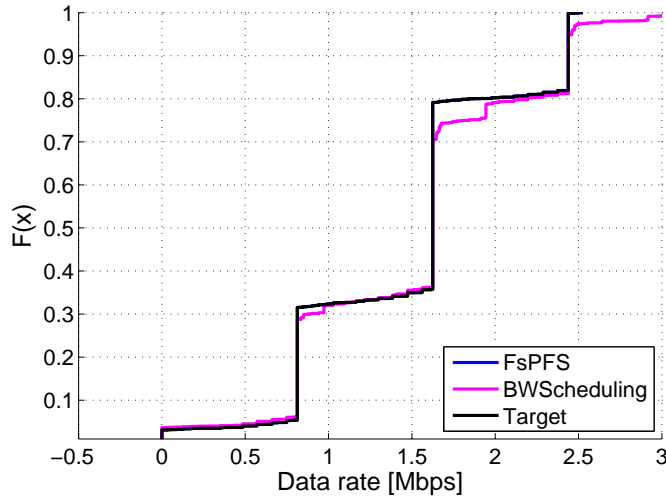


Figure 4.31: User data rate with low overhead, $\phi = 0.129$, and load for BWS

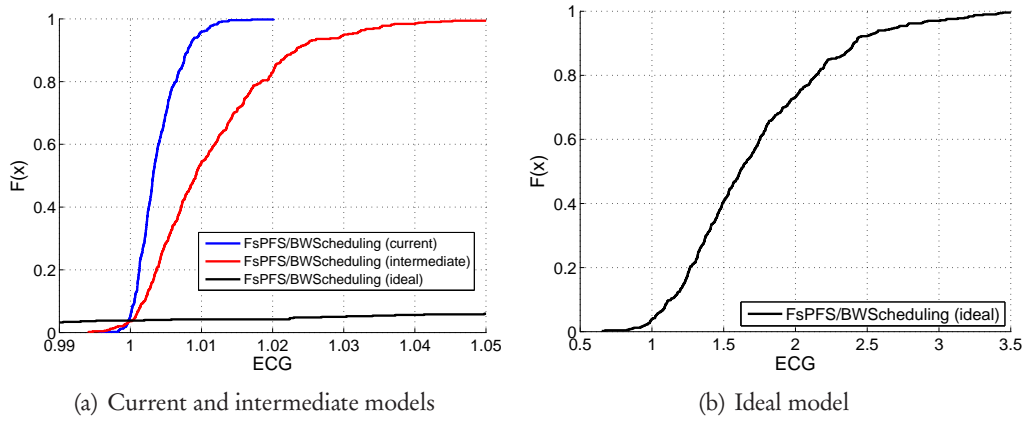


Figure 4.32: ECG with low overhead and load for BWS

at the 50th percentile is the same for the current and intermediate models, but is increased by 9.2% for the ideal one.

The RB interference level results for the low overhead scenario are presented in Fig. 4.33. The gap between the combined and benchmark systems is 1.4 dB in favor of the combined system. This is approximately the same as the BEM system, and higher than TCoM and EESBS by approximately 0.5 dB.

4.3.1.2 High overhead

The higher overhead, $\phi = 0.269$, leads to lower achieved user data rate as presented in Fig. 4.34. As desired, the benchmark and proposed combined systems achieve very similar user

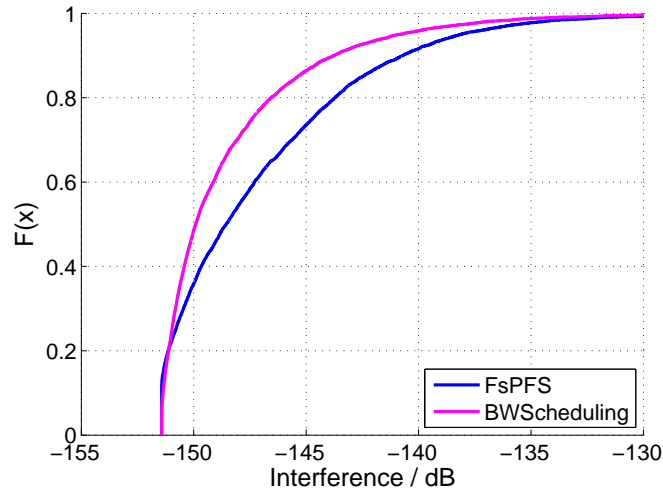


Figure 4.33: RB interference levels with low overhead and load for BWS

data rates. Yet again, those are not completely identical as approximately 15% of the user population achieves a marginally higher data rate in the BWS system.

The energy efficiency performance of the two systems can be found in Fig. 4.35. The combined system is able to achieve energy savings in 95%, 97% and 98% of the time for the three BS energy consumption models respectively. At the 50th percentile the reduction in energy is 0.2%, 0.7% and 20% respectively. Compared to the EESBS, BEM, and TCoM separate results, the BWS system performs significantly better than EESBS by delivering gains in an additional 10% of the time, slightly better than TCoM by 3 – 5%, and approximately the same as BEM. The gains for the current and intermediate models are approximately the same. However, for the ideal model, the combined system performs 5.3% better than EESBS, the same as BEM, and 2.3% better than TCoM.

Fig. 4.36 presents the interference levels per RB. The combined system is able to reduce the interference over the benchmark by 1.3 dB at the 50th percentile. This result is 0.5 dB better than the pure EESBS system, comparable to the one achieved by the BEM system, and 0.3 dB better than the TCoM one.

4.3.2 Rate un-matched results

After assessing the energy efficiency performance in a like for like scenario, it is of value to see the unconstrained performance of the proposed combined system. The following results

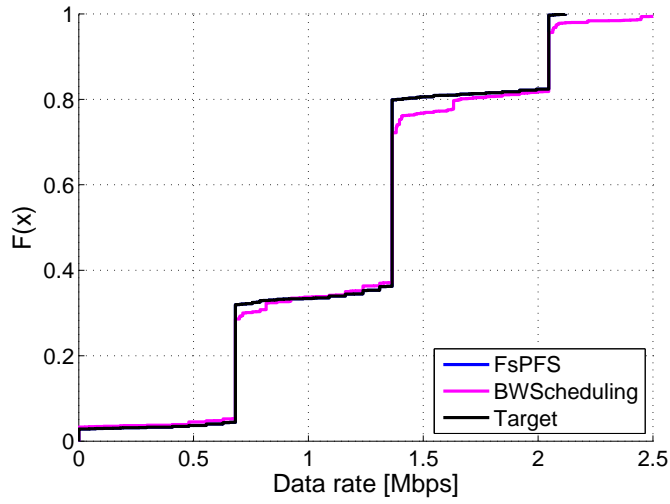


Figure 4.34: User data rate with high overhead, $\phi = 0.269$, and low load for BWS

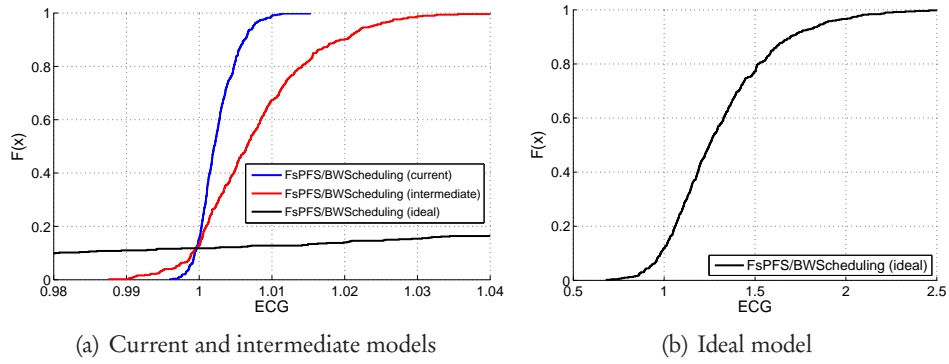


Figure 4.35: ECG with high overhead and low load for BWS

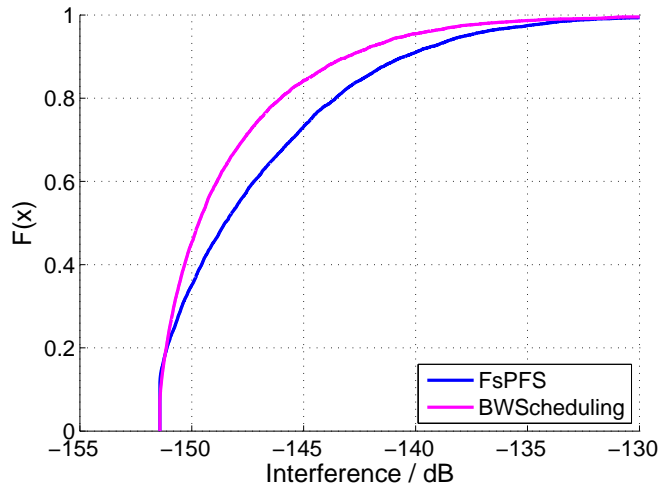


Figure 4.36: RB interference levels with high overhead and low load for BWS

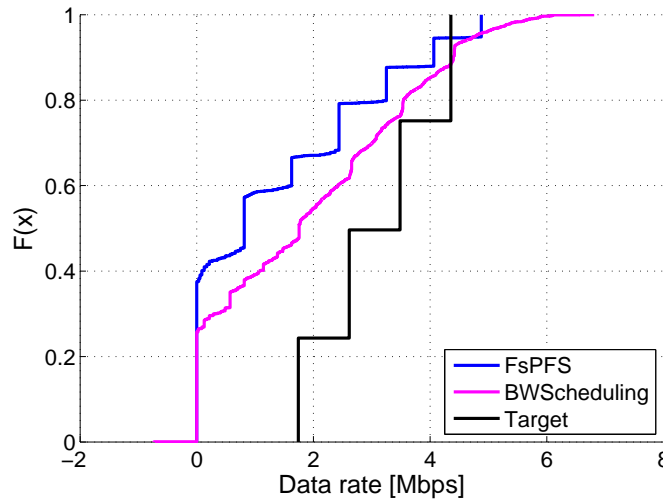


Figure 4.37: User data rate with low overhead, $\phi = 0.129$, and high load for BWS

are obtained in the scenario with low overhead, $\phi = 0.169$, and very high load where both systems are trying to achieve the best user data rates they are capable of.

The CDFs of the aforementioned achieved data rates are plotted in Fig. 4.37. The benchmark system is unable to serve 37.5% of its users compared to only 25.7% for the BWS system. The achieved data rate at the 50th percentile is 0.8 Mbps for FsPF and 1.75 Mbps for the proposed combined system. The BWS system performs significantly better than the benchmark in both categories. These results are almost identical to the ones achieved for the BEM and TCoM systems. The pure EESBS system is able to achieve slightly better outage percentage – 23%. The increase in outage is due to a small percentage of the changes in allocation effected by BEM and TCoM resulting in additional RBs in outage.

The average user data rate is plotted as a function of normalized distance from the BS in Fig. 4.38. Similar to the previously presented results, the combined system is able to outperform the benchmark for distances higher than 35% of the radius. For smaller distances, the performance of the benchmark system is better by approximately 5%. At 60% distance from the BS, the combined system achieves throughput of 3.1 Mbps, while the benchmark system delivers only 2 Mbps. At the cell edge, the BWS system achieves data rate of 0.8 Mbps against 0.4 Mbps for the benchmark system. These are significant gains at 55% and 100% improvement respectively. Compared to EESBS, BEM, and TCoM, the gains in absolute terms are approximately the same, any deviations are most likely due to differences in the random realizations evaluated in the simulation.

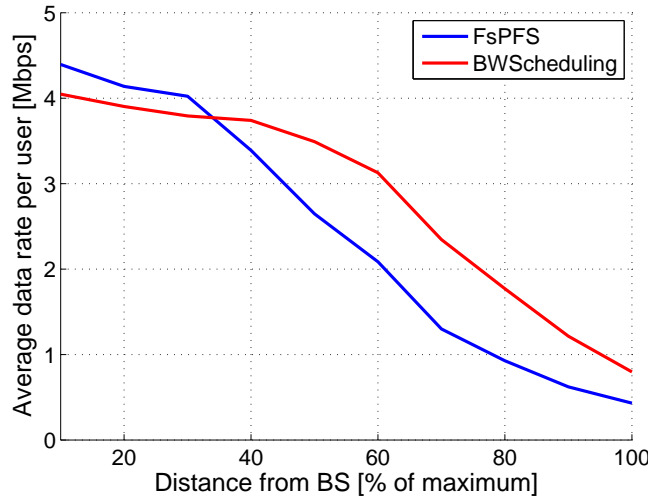


Figure 4.38: Distance vs. data rate for FsPF and BWS with low overhead and high load

Fig. 4.39 presents the ECG performance of the benchmark and proposed systems. The BWS system is able to provide energy savings against the benchmark for 23%, 21%, and 21% of the time for the different BS consumption models respectively. The energy consumption loss at the 50th percentile is 0.5%, 1.46%, and 27.4% for the three BS models respectively. Compared to pure EESBS, these results are significantly better. In terms of percentage of cases when energy reduction is achieved, the BWS system improves on EESBS dramatically, which is able to provide energy savings for less than 2% of simulation realizations. In terms of energy loss at the 50th percentile, the combined system is able to decrease the loss on average by approximately 4 times for the different hardware energy consumption models. The performance of the BWS system is also better than that of BEM. The percentage of simulation realizations when the system provides energy savings is approximately 4 times higher. Also the losses in energy efficiency at the 50th percentile are several times lower for the BWS system. Compared to TCoM, the percentage of simulation realizations which benefit from energy reduction is approximately the same, however, the loss in energy efficiency is smaller for all BS models, with the one for the ideal BS model being 15% lower for the BWS system. The combination of all three techniques into one system is able to retain the better achieved user data rate, while significantly improve on the energy consumption performance on the system compared to the stand alone scheduler, and the lone bandwidth management techniques combined with EESBS.

Following the ECG results, the CDFs of ECR for the benchmark and BWS systems are presented in Fig. 4.40. Once again, due to the emphasis on quiescent state drain in the current

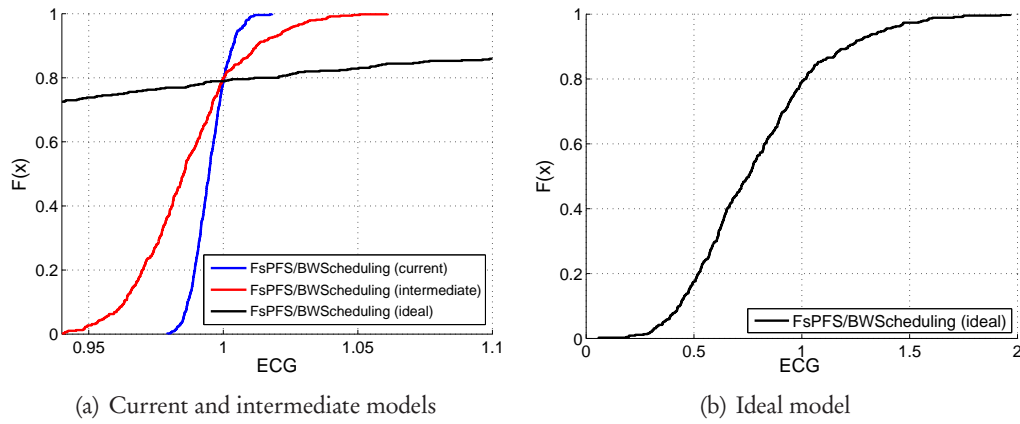


Figure 4.39: ECG for BWS with low overhead and high load

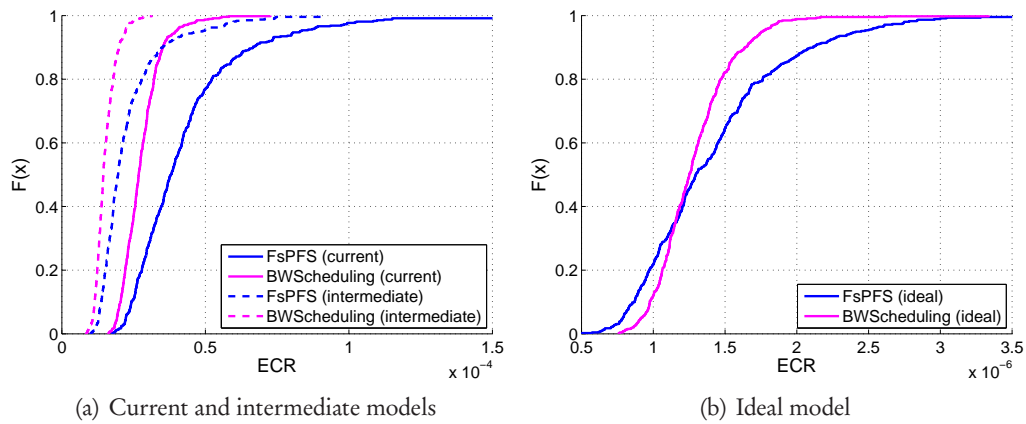


Figure 4.40: ECR with low overhead and high load for BWS

and intermediate models, the performance between EESBS, BEM, and TCoM is very similar for these models. However, for the ideal BS model, the BWS system is able to be more energy efficient than the benchmark in 65% of the cases which is an improvement of 15% over TCoM, and 65% more than what EESBS is able to achieve, since it never performs better than FsPF. Compared to BEM, this is an improvement of 60%. Clearly, the combined system is able to achieve better energy efficiency than its constituent parts, when evaluated separately.

The CDFs of interference per RB for the combined and benchmark systems can be found in Fig. 4.41. The difference in experienced interference at the 50th percentile is 1.6 dB in favor of the combined system. This is better than the results for EESBS and BEM, and in line with the results obtained for TCoM.

The BWS system is able to retain all the positives of the systems that make it up. It retains the

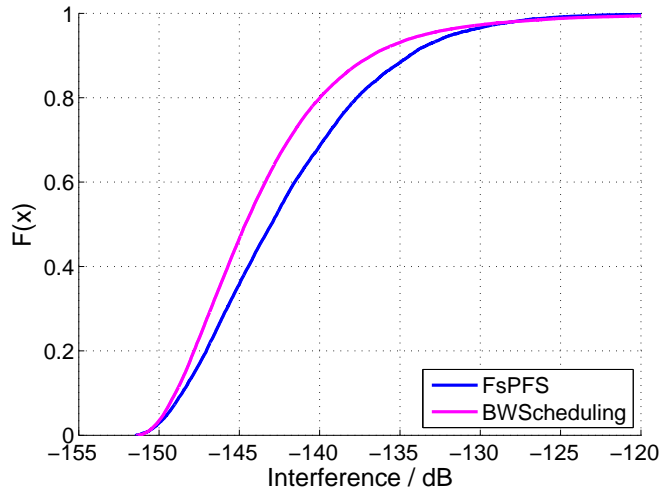


Figure 4.41: *RB interference levels with low overhead and high load for BWS*

high user data rate achieved by EESBS, along with higher energy savings than the BEM and TCoM systems are able to achieve on their own. In the high loading scenario, it maintains the favorable performance that TCoM achieves on its own in terms of percentage of the time a gain in ECR is provided, but is able to increase the gain at the 50th percentile by approximately 15% due to the favorable combination of BEM and TCoM.

4.4 Summary

In this chapter, two techniques to manage bandwidth allocated to the users are introduced – BEM and TCoM. They are both designed to work together with a smart, energy and channel aware scheduler like EESBS. Their goal is to reduce energy consumption without compromising the delivered data rate to the user.

BEM operates by expanding a user's bandwidth while preserving the achieved user transmission rate, and hence reduces the overall energy consumption. Theoretical analysis of the technique shows that it is effective for scenarios where the starting modulation order is high *i.e.* high SINR target, the overhead is low, and the BS is experiencing high RF transmission power load. This means that the target demographic of users that stand to benefit from BEM is ones with high data rate requirements whose energy consumption is dominated by data transmission energy. The simulation results for the different scenarios show energy efficiency gains in over 85% of cases with up to 36.6% better performance at the 50th percentile. The gain is

highly dependent on the BS energy consumption model. The current and intermediate models restrict the gain to an insignificant value. However, the ideal BS model allows the system to deliver the highest energy efficiency gains it is capable of.

Comparing BEM behaviour in scenarios with low and high energy overhead due to control signaling, the system performs the same in terms of achieved raw user data rate. However, the energy efficiency gains that are achieved over the benchmark are significantly reduced in the high overhead scenario. When comparing the rate matched results against the rate unmatched ones, it emerges that BEM can either grant energy savings over the benchmark system while the required user data rate is within the capabilities of the benchmark or improve the delivered user data rate. This provides a flexibility not achieved by the benchmark system. For the intermediate and current BS models, the improvement in data rate is achieved with better energy efficiency in terms of bits per unit energy. However, this is not true when the ideal hardware model is used.

TCoM is targeted at reducing the energy consumption of users whose energy expenditure is dominated by overhead transmissions. Such users are likely to be experiencing good channel conditions and require low transmission data rate. The technique reduces the user's bandwidth while preserving the achieved data rate, hence reducing the energy expenditure due to the overhead. It is shown that theoretically it performs best in scenarios with high overhead and low starting modulation order. Through simulation, it is shown that TCoM is able to deliver energy gains in over 88% of simulation realizations, as well as up to 28.9% reduction of energy consumption at the 50th percentile. Again, the used hardware model has a critical role in determining the amount of gain achieved.

Unlike BEM, the behaviour exhibited by TCoM improves with higher overhead. The performance gap between EESBS and TCoM widens in favor of TCoM with the increase of overhead. Similar to BEM, the combined TCoM and EESBS system is able to either provide energy savings or improve the achieved data rate with some detriment to the overall energy consumption. In the case of the current and intermediate hardware models, this detriment is very small and on the order of 5% at most. Unlike BEM, TCoM is able to provide both energy efficiency gains and the higher data rate in slightly more than 20% of the time for all the hardware models used.

Finally, a combined system comprising of both techniques described in this chapter, BEM and

TCoM, as well as the necessary EESBS scheduler, is tested in the various scenarios to evaluate its performance potential. It is able to provide energy savings for over 96% of the time as well as up to 38% reduction in energy expenditure at the 50th percentile of ECG.

The BWS system behaves similar to BEM when it comes to the effect of overhead. The system performs better in the simulation scenario with lower values of overhead. Overall, it performs better than the pure EESBS and the combined with EESBS BEM and TCoM systems. The performance gap is largest when rate matching between the proposed system and the benchmark is not enforced. The combined system outperforms all the proposed systems both in terms of the percentage of time it is able to provide energy savings, as well as being able to minimize the loss in energy efficiency at the 50th percentile. Although, overall the system uses more energy on average, in terms of delivered data bits per unit energy, the system outperforms the benchmark when the current and intermediate hardware models are applied. When the ideal BS model is used, the BWS system is more efficient in approximately 65% of the time even though it delivers significantly higher data rates to the users.

Overall, the combined system has the best performance as expected. It is able to deliver significantly higher data rates to the mobile users without sacrificing energy efficiency significantly, and in most cases actually augmenting it.

Chapter 5

Harnessing User Mobility to Enhance Energy Efficiency

ALL of the techniques proposed in the previous chapters are able to deliver substantial energy reductions. However, those gains are highly dependent on the underlying base station (BS) hardware model. This chapter presents a technique that exploits user mobility patterns to allow BS hardware to turn on and off in a synchronized manner with traffic load, and achieve energy reduction with minimal loss in data rate performance and no erratic BS behaviour. Most importantly, the technique is targeted at achieving significant gains with the hardware consumption model that reflects the state of BSs today.

The rest of the chapter is organized as follows. Section 5.1 introduces a realistic user mobility model. Section 5.2 describes the operation of the proposed energy efficient BS control algorithm, or energy efficient hardware state control (EESC) for short. Section 5.3 derives a theoretical expression that approximates the energy reduction gain that is expected. Section 5.4 presents the simulation platform used for empirical testing, and the results that are obtained. The chapter is summarized in Section 5.5.

5.1 Mobility Model

Before devising a scheme that exploits user mobility, and the resulting variations in load, to achieve energy savings, the behaviour of users has to be modeled accurately. Over long period averages, people generally have stable movement patterns [106]. This is why a simple probabilistic movement model over a set of locations should produce results that are close to what is observed in the real world. The randomness is introduced in the ability of the user within the model to change location based on a probability function.

Two locations are considered – home and work. A probabilistic model governs the movement

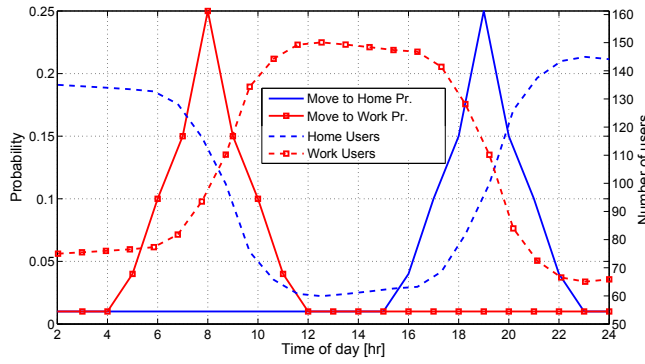


Figure 5.1: User distribution vs time

between these two locations. Users start at either of the two locations with a probability of μ and $(1 - \mu)$ for home and work, respectively. From then on, a user's location is re-evaluated every hour based on the movement probability curves that can be found in Fig. 5.1. If the user is currently at the home location, then the curve that is labeled move to work probability, gives the probability that the user moves to the work location as a function of the time of day. The reverse movement probability is described by the move to home probability curve on the graph. The curves were generated taking into account that the generally accepted working times are 9 AM to 5 PM. Time was allotted for commuting, as well as social interaction in the evenings [107]. Unfortunately, it is not possible to use real measurements as those are not readily available. What little is available is either focused on different metrics and/or outdated [108, 109].

If 210 users were to be placed between the two locations with $\mu = 0.65$, the user distribution over time for the two locations that is presented in Fig. 5.1 is one possible random realization. The value for μ , is chosen such that it models the fact that at night there usually is a higher congregation of people in residential neighborhoods. This user density as a function of time is a reasonable model for user mobility between a residential and place of business locations as it adheres to the findings in [106].

It is important to note that this model is not based on any rigorously analyzed real world data. It only reflects a basic principle of movement between home and work locations and is loosely based on data like usual working hours. Moreover, it does not model the variation of use that is present as a function of the day and was presented in the chapter 1. As such, this model only represents a very limited user case and is in no way universal. In light of that, all results need to be viewed as more of proof-of-concept rather than real-world applicable gains.

5.2 Infrastructure Power State Control Model

Any BS power state control algorithm has to be designed to take into account the particularities of the hardware it is to operate upon, and in the case of a cellular communication network – also the user population that is to be served. This is why both a reliable model for the energy consumption behaviour of BSs and a representative user movement model have to be used while the EESC algorithm is designed.

The hardware efficiency model for current BSs presented previously in chapter 2 is biased towards quiescent state drain, hence it promotes the turning off of BSs over optimization of energy expenditure on the radio frequency (RF) side. Hence, the following hardware state control algorithm is proposed. A BS is allowed to turn off if and only if the following conditions are met:

1. The BS is not expecting a load higher than ζ percent of the current load in the next hour.
2. The users connected to the BS can be handed off to nearby BSs with a maximum loss of ψ percent in overall data rate.

In order to be able to enforce the first condition, the load behaviour is observed first for a learning period of x days. During that time a loading profile for each BS in terms of normalized load to maximum load versus time of day is created. This profile is of the form of the already presented one in Fig. 1.8, and is used to look up the expected load for the BS. The observance of the first rule allows the system to avoid any erratic turning on and off of the hardware. A behaviour that is possible in systems that control the state of BSs solely based on the current load. The second rule makes sure that the experienced loss in throughput is within tolerable limits. In practice, the latter rule can be implemented based on the receiver signal strength indicator (RSSI) of the BS that the user is to be handed off to, and would not require full channel knowledge.

5.3 Theoretical Performance Model

The theoretical gain from employing the technique outlined in this chapter against a system that keeps all BSs always on can be easily approximated if several assumptions are made. The

first assumption to make is that on average, the load experienced at any of the two considered locations is proportional to the number of users at that location at the time. Second, if energy usage follows load in the proposed system, then we can assume that in an ideal case only a percentage of the BSs equal to that of the current load (normalized to maximum possible load) need to be operational. Of course, this is not strictly true in practice due to problems of cell coverage as well as non-homogeneous user data rate requirements. However, it is necessary to make these assumptions so that a theoretical closed-form model can be built to approximate the performance of the system.

In order to calculate the energy consumption gain (ECG) performance of EESC, a point of reference in the form of a benchmark system is required. Within the theoretical model, the proposed system is compared to a system that keeps all BSs on all of the time. This benchmark system is henceforth referred to as FULL. Choosing the FULL system as a basis for comparison makes sure that we compare two systems that achieve very similar user throughput. In turn, this means that the analysis of the two systems' energy efficiency performance is meaningful. With the benchmark established, the derivation of the theoretical model can begin.

If $u_H(T)$ and $u_W(T)$ are the number of users at each location at time T in hours, then the load at the two locations can be approximated by $l_H(T) = \frac{u_H(T)}{u_{\max}}$ and $l_W(T) = \frac{u_W(T)}{u_{\max}}$, where u_{\max} is the maximum number of supported users at any one location. Hence the energy used at each location due to the BSs' quiescent drain becomes:

$$E_{\text{FULL}} = 2n_{\text{BS}}P_{\text{BS},0} \quad (5.1)$$

$$E_{\text{EESC}} = (l_H(T) + l_W(T))n_{\text{BS}}P_{\text{BS},0}, \quad (5.2)$$

where n_{BS} is the number of BSs at each location, home or work, and the FULL subscript refers to the benchmark system. The above can be used to compute the energy comparison gain (ECG) of the proposed dynamic system versus the always on, full infrastructure, benchmark:

$$\text{ECG} = \frac{E_{\text{FULL}}}{E_{\text{DYN}}} = \frac{2}{l_H(T) + l_W(T)} \quad (5.3)$$

A plot of (5.3) can be found in Fig. 5.2. As intuition suggests, the gains increase as the overall loading in the system decreases. EESC is able to turn off more BSs as the load decreases, and hence saves more energy.

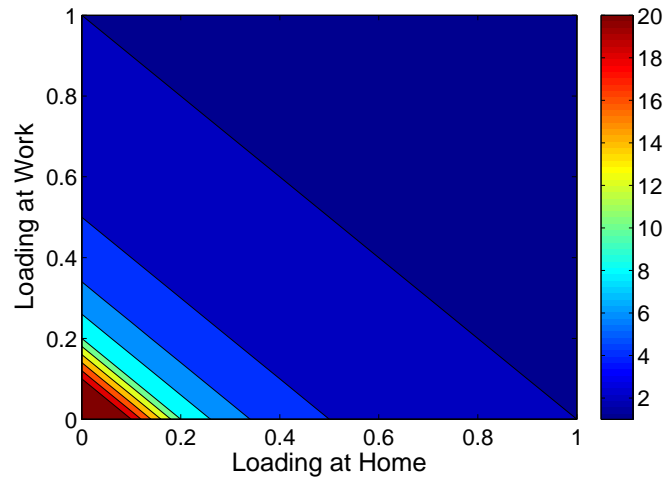


Figure 5.2: *Theoretical ECG as a function of loading for EESC*

If the energy consumption due to the RF transmissions is to be accounted for as well, equation (5.3) becomes:

$$\text{ECG}_{\text{RF}} = \frac{2n_{\text{BS}}P_{\text{BS},0} + \Delta_p P_{\text{BS},\text{out}}^{\text{total}}}{(l_{\text{H}}(T) + l_{\text{W}}(T))n_{\text{BS}}P_{\text{BS},0} + \Delta_p P_{\text{BS},\text{out}}^{\text{total}}}, \quad (5.4)$$

where $P_{\text{BS},\text{out}}^{\text{total}}$ is the total required RF power in the system considering both the home and work locations. The increase in RF energy consumption due to the handover of users in the EESC system is omitted. This component is very difficult to model accurately, as there is strong interdependence due to interference. The situation is similar to that already outlined for the theoretical model of energy efficient score-based scheduler (EESBS). User location and channel conditions play an important role as well, and are specific to each random scenario realization. Hence, no attempt has been made to include it in the model, as a crude approximation will not grant any significant additional insight.

The expression is plotted in Fig. 5.3. The figure representation makes it easy to realize again that there are high gains to be had when the load is low, since more BSs can be turned off. The addition of the RF power consumption component reduces the ECG as there is higher demand in the system for RF power. This stems from the fact that the dynamic, RF, portion of the consumption increases, while the proposed algorithm can only control the quiescent consumption, by turning off BSs. Hence, the overall gain is reduced since a smaller percentage of the overall BS energy consumption can be controlled by EESC.

Currently a BS's energy consumption is dominated by the quiescent drain, which is a signif-

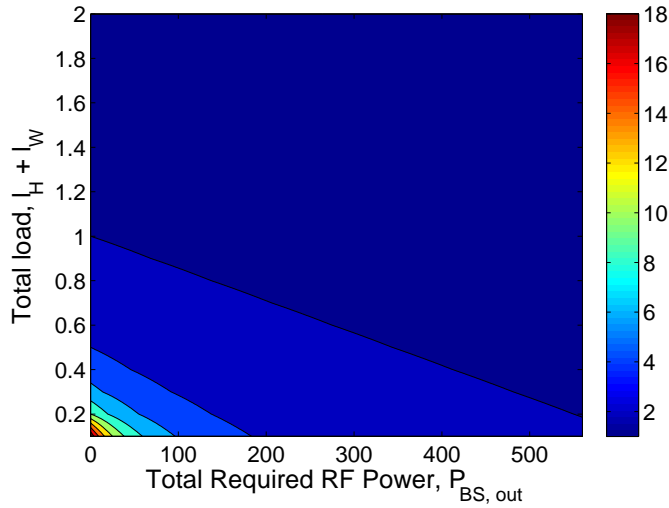


Figure 5.3: *Theoretical ECG as a function of user loading and required RF power for EESC*

ican part of the maximum possible energy drain of the cell site. For example, in the model that represents current BSs, the quiescent drain is 712 W, and the dynamic drain due to RF communications can be up to 580 W at its peak. Due to the nature of the control algorithm, energy consumption increases in the dynamic portion due to handovers will only be important in low load periods when the load of the system is expected to be less than 50%. This is the case because it is at those times that a significant number of BSs could be turned off and their users handed over to other nearby cells. In those cases, the dynamic consumption will only represent 29% at most of the total energy consumption of the BS. Even a significant increase by 20% in the required RF power at that time will only result in an overall increase of used energy of less than 6%. This significantly diminishes the error in the theoretical model due to not considering the fluctuation of the total dynamic energy consumption of all the BSs caused by the handover of users between them.

5.4 Simulation Results

An LTE based simulator, derived from the one described in Chapter 3, is developed to evaluate the performance of EESC. Within the simulator platform three systems are evaluated – EESC, the already introduced full infrastructure benchmark (FULL), and a second benchmark (MIN) that only uses the three sectors of each location’s central BS cell to cover the target area. In the second benchmark, all other BSs are turned off, and users are connected to the three remaining operational sectors of the central BS. The three sectors in the central cell are then extended

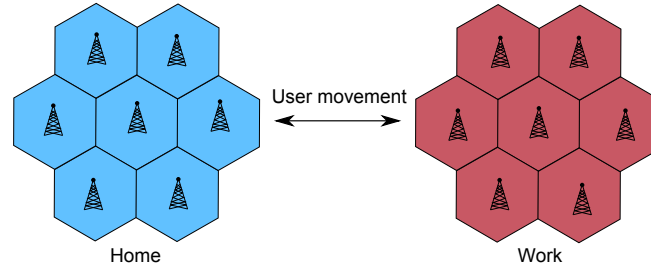


Figure 5.4: *System scenario topology*

to cover the entire target area. All systems are identical to each other except for the way they allow the BSs to be operational or not.

5.4.1 Simulation System and Scenario

The system scenario of choice is again a cellular system. A central cell with one tiered deployment is used to simulate each of the two areas. A smaller scenario is used here in order to reduce the computational time. A figure of the simulated scenario can be found in Fig. 5.4. Each cell consists of three non-overlapping sectors. The reduction in the number of cells that are simulated leads to less realistic interference distribution, which in turn means that the RF energy consumption and the achieved data rates will be less realistic.

Users are initially distributed between the two locations based on the initial probability of location, μ . Then, they are allowed to move between locations based on the probability density functions in Fig. 5.1, which results in the example user distribution versus time in the same figure that was already discussed.

The channel model used is the LTE urban micro-cell (UMi) [98] as defined in Table 3.2, where d is the distance between transmitter and receiver, f_c is the carrier frequency in MHz, h_{BS} is the elevation of the base station (BS) antenna, and h_{UT} is the elevation of the user terminal antenna. In practice one of the three path loss equations is selected, based on d .

The fast fading channel model based on (3.6) and described in Chapter 3 is used.

Adhering to the simulation framework used for the testing of the EESBS, bandwidth expansion mode (BEM), and time compression mode (TCoM), the Foschini-Miljanic simple power control algorithm is used. Power control is even more important while testing EESC since the process of handing-off users from one BS to another inherently forces a change in the

Table 5.1: *System Parameters*

Parameter	Value
Total Bandwidth	18 MHz
Carrier Frequency	2.14 GHz
Resource Bandwidth	180 kHz
Number of Resource Blocks (RBs)	100
Subcarriers per RB	12
Noise Floor	-121.42 dBm
BS Maximum Power	46 dBm
Antenna gain	10 dB
User Speed	3 km/h
Target data rates	2, 4, and 6 Mbps
Inter-site distance	1000 m
Initial home location probability, μ	65%
Percent higher load allowed, ζ	20%
Percent loss in data rate allowed, ψ	5%
Learning period, x	100 days

transmission RF power level.

An infinite size buffer traffic model is used to make sure that all users contend for transmission all of the time. Each user is randomly assigned a target data rate from a uniformly distributed discrete set of rates, and tries to transmit all the time since it has an infinite sized buffer of data to transmit. The data rates in the set can be found in Table 5.1.

The downlink transmission direction is simulated. Data is collected from one time slot after the system has settled to a stable resource allocation.

A frequency selective proportional fair (FsPF) scheduler as the one discussed in the Problem Formulation section of [97] is used in all three systems. The FsPF scheduler operates by applying the proportional fair principle to each RB at a time, and allocating each RB to the user who maximizes the fairness ratio. To avoid initial allocation conflicts, the order in which RBs are considered within each BS is randomized.

All system parameters are listed in Table 5.1. The value chosen for the initial home location probability is such that it reflects the assumption that residential areas generally have higher number of people staying there overnight. The percentage loss allowed in data rate is chosen such that the loss in data rate due to employing EESC is low. Lastly, the percent higher load allowed is a value chosen such that it allows the system to turn off BSs for a large part of the day.

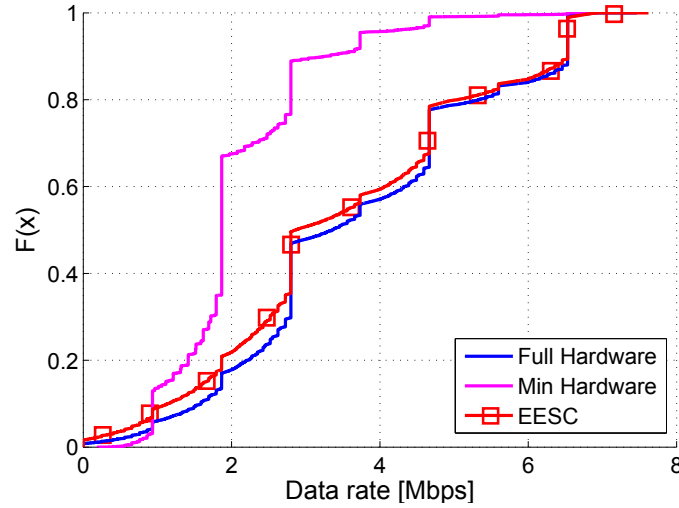


Figure 5.5: *CDF of user data rate for EESC*

Any details with regard to the simulation platform not explicitly stated here should be taken from the previously described simulator.

5.4.2 Results

Using the simulation platform described in the previous section, several sets of parameters are evaluated for 100 random simulation realizations each, and statistics on the performance of the three systems collected.

Fig. 5.5 presents the CDF of user data rate for a total of 245 users in the system. The proposed system behaves as a middle ground to the FULL and MIN benchmarks. The minimum hardware system is able to provide approximately 1.9 Mbps at the 50th percentile, whereas the EESC and FULL systems provide approximately double that. In general, the decrease in data rate performance that the proposed dynamic system experiences compared to the maximum hardware one is minimal, and can be adjusted by changing the ψ parameter.

Fig. 5.6 presents the required input power as a function of time. It is clear that the proposed system is able to follow the transfer of load between the two locations very well, and hence provide energy savings. Contrary to that, the FULL and MIN benchmarks present seemingly constant energy consumption at both sites over time, which means they do not react well to the transfer of users from the home to the work location and vice versa.

Fig. 5.7 provides additional information on the energy consumption behaviour of the two

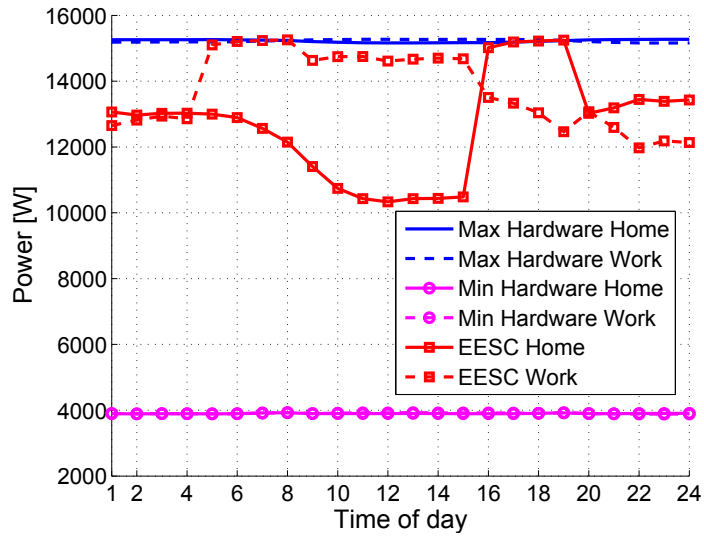


Figure 5.6: Total power consumption versus time for EESC

benchmarks. Both systems do respond to the variation in load in the two locations with changes in their energy consumption. The FULL system clearly experiences a difference in energy consumption that corresponds to the movement of the users. However, the change is small compared to the overall consumption since it is only due to the change in RF energy load. The MIN system also shows variation of required energy with time. However, its behaviour is a lot more erratic and harder to correlate with the change in loading. This is due to the high load the central cell experiences all the time, as well as the non-constant distribution over time of users connected to it in terms of distance between the BS and themselves. Still, the same general behaviour of the energy consumption visible in the results for EESC and FULL can be observed for the MIN system. The notable deviations are in the transient periods when users move from one location to the other.

Fig. 5.8 presents achieved average ECG as a function of the total number of users in the system. The results are consistent with the behaviour observed in the theoretical results – the gain decreases very quickly as the total load in the system is increased. The reduction in energy consumption achieved by the proposed system over the always on benchmark, FULL, ranges from 36% to 11%. A reduction in energy efficiency of approximately 3 times is caused by an increase in user population of 4.5 times.

In order to investigate the effects of ζ and ψ on the system behaviour, several combinations of these parameters are evaluated and the average ECG results are presented in Fig. 5.9. The

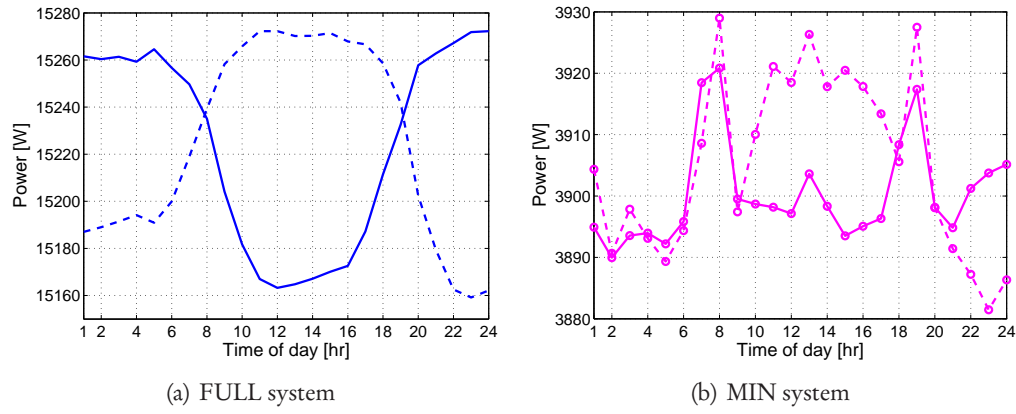


Figure 5.7: Separate plots of total power consumption for EESC benchmarks, legend same as in Fig. 5.6

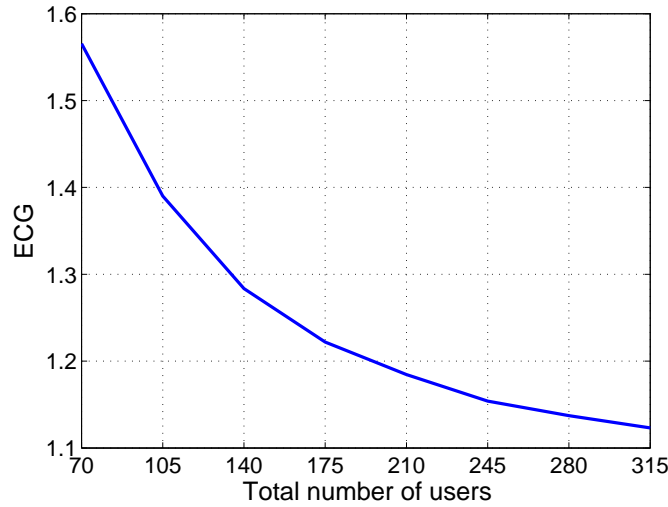


Figure 5.8: Empirical average ECG of $E_{\text{FULL}}/E_{\text{EESC}}$ versus load

simulations are performed with a population of 245 users. Both parameters affect the energy efficiency performance of EESC. The percent higher load allowed, ζ , has a less pronounced effect. Its effect on the energy savings accrued in the system is limited by ψ . Although, in principle, the higher it is, the more aggressive EESC can be at turning BSs off, in practice, the BSs cannot be turned off if the datarate loss exceeds ψ . This clearly is represented in the results, since higher values for ψ allow for a larger variability in the achieved ECG by changing ζ . The theoretical prediction that the higher loss in data rate allowed, the better the energy efficiency will be is backed up by the empirical simulation results. The ψ parameter allows for a direct trade-off between energy efficiency and user data rate.

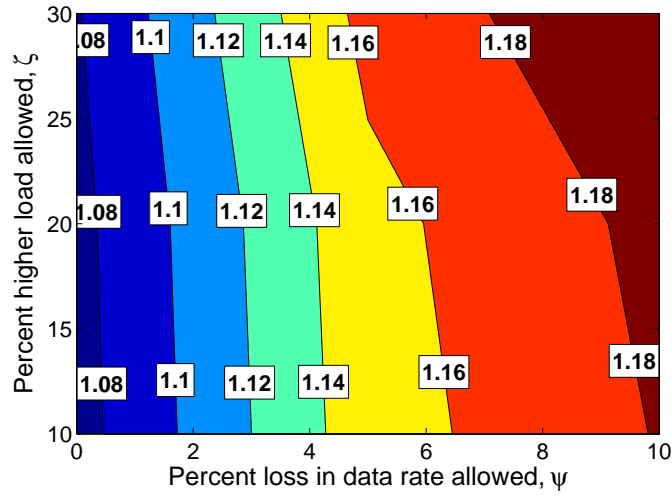


Figure 5.9: Empirical average ECG of $E_{\text{FULL}}/E_{\text{EESC}}$ for different parameter combinations

The mean loss in total user data rate that complements Fig. 5.9 can be found in Fig. 5.10. As intuition suggests, as ψ is increased, the mean loss in the sum user data rate increases linearly. The ζ parameter exhibits little effect over the loss in total user data rate.

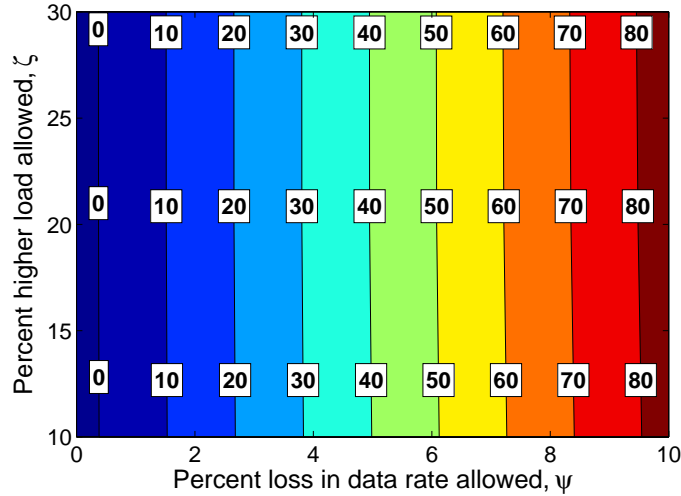


Figure 5.10: Difference in the mean of sum user data rate, in Mbps, between the EESC system and the benchmark for different parameter combinations

The simulation results presented above lead to several important conclusions. EESC can be a powerful tool in scenarios where the mobility of users from one location to another is high leading to large swings in loading throughout the day. Changes in both the higher load allowed, ζ , and loss in data rate, ψ , affect the energy savings achieved. The effects due to ψ are more pronounced. However, ζ has little effect on the mean loss in sum data rate, making it

the parameter that can be adjusted more aggressively to gain more energy savings.

5.5 Summary

In this chapter, a user mobility model that can be used to simulate user movement between two or more locations is introduced. Moreover, a simple novel algorithm for BS state control in a wireless cellular system, EESC, is outlined.

With respect to loading in the system, EESC delivers higher energy savings when the load is low. When there are only 70 users, the energy efficiency gain is 36%, but when the number increases to 315 – the gain is only 11%. However, these gains are only relevant to the particular mobility model. As outlined earlier this model is not universally applicable and should not be considered as representative of real life.

There are two parameters that control the behaviour of EESC – percent loss in user data rate allowed, ψ , and percent higher load allowed, ζ . Both have an effect on the energy efficiency performance of the algorithm. The higher the values for both parameters, the better the gains from EESC. High values of the parameters allow the system to be more aggressive in turning off BSs. It's important to note that trading-off data rate for energy efficiency is more effective in generating energy savings, than being more aggressive with regard to allowing BSs to turn off regardless of incoming load. However, ζ does not have an adverse effect on the loss in data rate. Hence, it should be the more aggressively adjusted parameter.

In general, the proposed EESC algorithm is able to turn off BSs that are experiencing low load and hand over any connected users to nearby BSs. Hence, it saves energy by utilizing the currently low impact of RF load on the BS overall energy consumption. Moreover, it does not lead to any erratic behaviour of the BSs, and is able to closely preserve the otherwise achieved user throughput.

Chapter 6

Summary and Conclusions

IN this thesis, four novel techniques have been introduced to enhance the energy efficiency in a wireless cellular system without explicitly sacrificing user throughput. Moreover, these techniques are compatible with each other, and their energy efficiency gains add up well without significant loss, as already demonstrated for three of them.

Chapter 1 introduced the context of the work, and the main motivations behind it. Chapter 2 presented background information that is essential to the understanding of this thesis, as well as the current state of the art in the field of energy efficient cellular wireless communications. Next, the concept of energy efficient score-based scheduler (EESBS) was introduced in Chapter 3. Two user bandwidth scheduling techniques, bandwidth expansion mode (BEM) and time compression mode (TCoM), that are designed to work with EESBS were introduced in Chapter 4 along with theoretical analysis and empirical results on their performance. The technical contributions of this thesis are completed with the addition of energy efficient hardware state control (EESC), an energy efficient base station (BS) power state control algorithm, in Chapter 5. This chapter concludes the thesis.

6.1 Main Findings

The first presented technique is the EESBS scheduler which is based on the score-based scheduling principle [94]. Unfortunately, there is no meaningful way to theoretically model both the user data rate and energy efficiency performance due to the tight coupling between users in terms of shared resources and interference. However, the empirical simulation results show that the scheduler is able to either improve the energy efficiency of the system or, if allowed, improve the user data rate dramatically at the cost of some energy efficiency. The proposed scheduler is able to provide energy efficiency gains up to 29% over the frequency selective proportional fair (FsPF) benchmark. Alternatively, it is able to decrease the number of users

in outage by 33% and increase the 50th percentile and cell edge user data rate by over 100%. Of course, the former comes at a cost of using more energy than the benchmark system. The energy efficiency gains, as well as losses in the rate unmatched case, are highly dependent on the applied hardware energy consumption model. Generally, energy consumption gains are achieved when the data rates between the benchmark and proposed system are matched. When the proposed system is allowed to achieve the highest user data rates it is capable of, it trades energy consumption for data rate, which results in higher energy consumption than the benchmark. However, it is important to note that the achieved user data rate is also significantly higher than the one delivered by the benchmark. The current and intermediate BS models allow for low gains and losses in energy consumption, whereas the ideal model generates high gains or losses.

The next novel technique is BEM which is used together with EESBS to improve the energy efficiency of the system. It expands a user's bandwidth when possible while preserving the achieved data rate. This enables the use of a more energy efficient modulation scheme, and effectively leads to lower overall energy consumption. Analysis shows that users whose energy consumption is dominated by data transmission rather than overhead are to benefit from the application of this technique. As expected, this leads to the system performing better in scenarios with low overhead. BEM is able to deliver energy savings of up to 36.6% over the benchmark at the 50th percentile, and deliver gains in general in over 90% of the time. In the rate unmatched scenario, the system retains the gains in user data rate achieved by pure EESBS, but at a lower energy cost. Again, the energy efficiency performance is highly dependent on the used BS model. Overall, BEM retains the flexibility of being able to save energy or increase user data rate granted by EESBS, while increasing the energy efficiency in all simulated scenarios.

To complement BEM, another system named TCoM is designed. It is targeted at reducing the energy consumption of users with high overhead. It cuts energy expenditure down by reducing the number of resource blocks (RBs) that are allocated to a user. This means that it is beneficial to users whose energy consumption is dominated by overhead transmissions, since the reduction in RBs allocated leads to an increase in the energy needed for the user data transmissions, as well as a decrease in the energy used for overhead communication. As a result of this, TCoM performs better in scenarios with high overhead relative to the other systems. It is able to achieve energy efficiency gains of up to 28.5% at the 50th percentile, and

deliver some gains for more than 80% of the time. In the rate unmatched simulation scenario, it achieves the same data rate gains as the two aforementioned systems, but at energy losses lower than both of them.

A system that combines all of the aforementioned techniques – EESBS, BEM, and TCoM, named bandwidth scheduling (BWS) is also evaluated. It also combines all the strengths of its constituents – EESBS allows it to achieve superior user data rates than the used FsPF benchmark, when the system is required to do so. When equivalent data rates are enforced between the proposed and benchmark system, BWS is able to deliver the required throughput much more efficiently in terms of required energy. It is able to grant energy savings up to 38.6% at the 50th percentile, as well as gains in general more than 95% of the time. In the unmatched rate simulation scenario, BWS once again achieves the same data rate gains as the other systems since it features EESBS. However, it is able to achieve only a 27.4% energy loss for the ideal BS model at the 50th percentile. Moreover, it delivers the enhanced data rate in a more energy efficient manner than FsPF 100% of the time for the current and intermediate models. For the ideal model, it does so for approximately 65% of the time. This is significant particularly for the current and intermediate hardware models, since BWS grants an increase of over 100% in user data rate not only at the 50th percentile but also at the cell edge for an increase of less than 5% in used energy.

Lastly, EESC is an algorithm which controls the power state of each BS in a cellular system based on the expected load. EESC is able to exploit the broadly predictable patterns of movement of users between a few locations in their daily routine. The presented case study focuses on two locations – home and work. The existence and predictability of the user patterns allow the system to have an awareness of when and how much capacity will be required in the immediate future. In turn, this is exploited to turn off BSs which are likely to experience low loads, and their users are handed off to nearby cell sites. Unlike the aforementioned systems, EESC is able to generate significant gains in energy efficiency with the current hardware energy consumption model. In simulation, the system achieves energy efficiency improvements up to 36% for a scenario with a low number of users. The gain comes with a small loss in user data rate that is controllable by the ϕ parameter. Simulation with different parameters shows that the higher the allowed loss in user data rate, the more aggressive EESC can be in turning off BSs and as a result more energy is saved. The gain from EESC can also be controlled by use of the maximum load increase parameter, ζ . Although the system is not as sensitive to

changes in ζ as in ψ , increases in ζ also allow the system to be more aggressive in turning BSs off and save additional energy without significant loss in data rate.

6.2 Limitations of Work

As with any work that is not directly applied in a real life scenario and tested, there are limits to the accuracy of the obtained results. Both the theoretical and simulation results presented so far have limitations that need to be considered.

The theoretical models presented so far do not account for the dynamic behaviour of the system. Every change in the radio frequency (RF) transmission power level leads to further subsequent changes in it in the respective direction. This is an effect akin to the cocktail party effect, where the voice level required to hold a conversation increases as more and more people arrive since the combined level of noise increases. Of course, the reverse process is also relevant, where the required voice level for conversation decreases as the overall noise level decreases as well. Both processes are self reinforcing *i.e.* once the levels start to decrease or increase the relevant movement increases the magnitude of the perturbation. Unfortunately, to theoretically model these effects is very difficult, and as a result they have not been incorporated in the theoretical models.

Another down side of the theoretical models presented in this thesis is that they generally model the best application of the proposed algorithms, which in practice is not true. For example, when the BEM system is trying to expand users' bandwidth, not all users will benefit from the bandwidth expansion. The theoretical model does not account for that and instead assumes that all users are going to benefit in a reduction of used energy if their bandwidth is expanded.

The simulation results are also not exempt from inaccuracies. First of all, the results are only as good as how applicable to the real world the simulation scenario is. Moreover, the aforementioned results are also only as good as the basic models that make up the simulation platform. While the channel models are also verified by measurements as part of the research process within the 3rd Generation Partnership Project (3GPP) and Wireless World Initiative New Radio (WINNER), parameter correlation with respect to location within the scenario topography is not implemented.

Another thing to consider is that omni directional antennas are used within the first simulator platform. This means that in the evaluation of EESBS, BEM, TCoM, and BWS, there was no regard for cell sectorization which is the norm in deployed networks. The reason to not consider sectorization is that the simulation run time for that particular study is very high as it is, and the inclusion of sectorization would increase the required simulation time significantly making it infeasible to obtain all the results presented.

In general, there is a lot more than can be done to enhance the real life applicability of the simulation platform. User mobility can be increased leading to incorporation of hand-off between nearby cells. The traffic model can be exchanged for a more realistic one. Lastly, indoor users can be incorporated in the scenario.

6.3 Outlook

This thesis certainly leaves additional research avenues that can be further pursued. The most obvious one is to evaluate the performance of a system that combines all the proposed algorithms in this thesis against a benchmark that is similar in performance to the currently deployed cellular networks.

Moreover, there are possibilities to extend EESBS. Within the score calculation subroutine, it is possible to alter the way that scores are calculated according to Fig. 3.1. All possibilities should be exploited and the difference in results analyzed in order to qualify the different score calculation sequences in terms of their performance. It is possible that one of the alternative score calculation methods could prove to be more energy efficient or provide better user data rate gains.

Also it is possible to take a more heuristic approach to evaluating the decisions made by EESBS. The current implementation relies on making each decision based on the incremental energy saving it provides. This is not necessarily the best approach. It is conceivable that a heuristic could be calculated instead that is better able to predict which choice is likely to benefit the system the most overall.

The effects of the penalty function definition have also not been studied in EESBS. Apart from studying different penalty functions, it could be of interest to see the effects of user or group specific penalty functions within the system. It might be possible to tailor specific

penalty functions to different types of users to enhance the overall system performance in terms of both capacity and energy efficiency.

The EESC system also has room for development. Currently the system only relies on local information, whereas it could use information from nearby cell clusters to predict future loading. This approach should prove to be more accurate than purely relying on statistical data. Also, no results on how the performance of the system changes with the learning period or the BS hardware energy consumption model are presented. This could also prove to be an interesting avenue of research.

In a more general approach, other avenues of research could potentially exploit machine learning techniques more fully. For example, genetic programming could be used to arrive at interesting scheduling solutions that could be further enhanced with human intervention. This could potentially be very useful in improving on the EESC results.

Another great machine learning tool is fuzzy logic. That could be used in coming up with techniques similar to EESBS and its extensions BEM and TCoM. Fuzzy logic is a particularly good fit in this type of problem as it generates solutions from a qualitative description by generating the required quantitative solution. Hence, it could be very interesting to design a scheduler that is based on fuzzy logic.

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ENERGY EFFICIENCY IN COMMUNICATIONS

Green Radio: Radio Techniques to Enable Energy-Efficient Wireless Networks

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ABSTRACT

Recent analysis by manufacturers and network operators has shown that current wireless networks are not very energy efficient, particularly the base stations by which terminals access services from the network. In response to this observation the Mobile Virtual Centre of Excellence (VCE) Green Radio project was established in 2009 to establish how significant energy savings may be obtained in future wireless systems. This article discusses the technical background to the project and discusses models of current energy consumption in base station devices. It also describes some of the most promising research directions in reducing the energy consumption of future base stations.

INTRODUCTION

Given the worldwide growth in the number of mobile subscribers, the move to higher-data-rate mobile broadband, and the increasing contribution of information technology to the overall energy consumption of the world, there is a need on environmental grounds to reduce the energy requirements of radio access networks. A typical mobile phone network in the United Kingdom may consume approximately 40–50 MW, even excluding the power consumed by users' handsets. In developing countries direct electricity connections are not readily available, so Vodafone, for example, use in excess of 1 million gallons of diesel per day to power their network. Mobile communications thus contributes a significant proportion of the total energy consumed by the information technology industry.

From an operator's perspective, reducing energy consumption will also translate to lower operating expenditure (OPEX) costs. Reducing carbon emissions and OPEX for wireless cellular networks are two key reasons behind the development of the Mobile VCE Green Radio program.

For example, the U.K. operators Orange and Vodafone both aim to achieve significant reductions in CO₂ emissions in the next 10 years. The Green Radio program sets the aspiration of achieving a hundredfold reduction in power consumption over current designs for wireless communication networks. This challenge is rendered nontrivial by the requirement to achieve this reduction without significantly compromising the quality of service (QoS) experienced by the network's users. In order to meaningfully measure success, appropriate measures of energy consumption must be applied. For example, a reduction in radiated power is not of benefit if it is achieved at the expense of a greater increase in power consumed in signal processing or vice versa.

The Green Radio project is pursuing energy reduction from two different perspectives. The first is to examine alternatives to the existing cellular network structures to reduce energy consumption. The second approach, discussed in detail in the present article, is to study novel techniques that can be used in base stations or handsets to reduce energy consumption in the network. We present the background to the project. We move on to discuss base station modeling, which is a critical issue for the project. We then present three case studies that describe the energy savings obtainable from different techniques that can be employed on wireless links. Finally, we present conclusions to the article.

REDUCING ENERGY CONSUMPTION IN WIRELESS NETWORKS

The specific objective of the Green Radio program is to investigate and create innovative methods for the reduction of the total energy needed to operate a radio access network and to identify appropriate radio architectures that enable such a power reduction. The typical power consumption of different elements of a

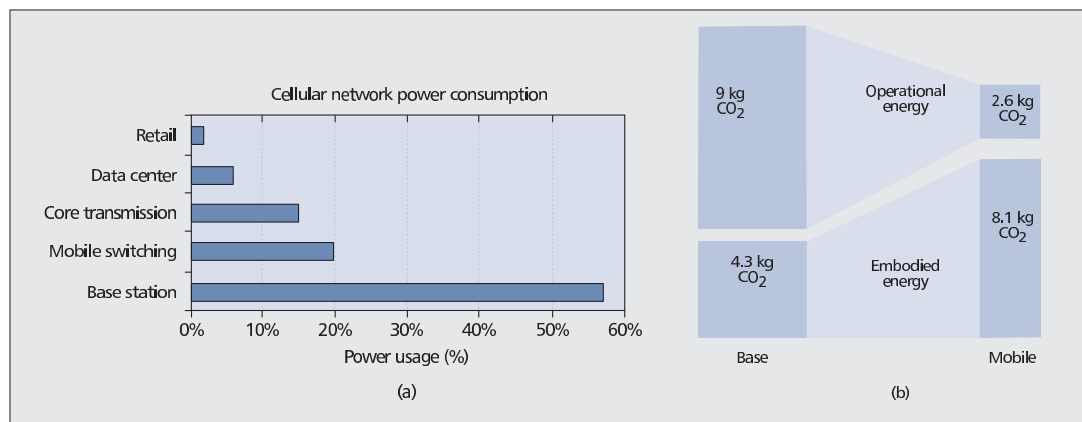


Figure 1. a) Power consumption of a typical wireless cellular network (source: Vodafone); b) CO₂ emissions per subscriber per year as derived for the base station and mobile handset, after [1]. Embodied emissions arise from the manufacturing process rather than operation.

current wireless network is shown in Fig. 1a. These results clearly show that reducing the power consumption of the base station or access point has to be an important element of this research program.

Studies have indicated that the mobile handset power drain per subscriber is much lower than the base station component, Fig. 1b [1]; hence, the Green Radio project will mainly focus on base station design issues. Figure 1b also shows that the manufacturing or embodied energy is a much larger component in the mobile handset than in the base station. This is because the lifetime of a base station is typically 10–15 years, compared to a typical handset being used for 2 years. In addition, the energy costs of a base station are shared between many mobile subscribers, leading to a large imbalance in the contribution of embodied energy. From the point of view of handsets, significant efforts need to be put into reducing manufacturing energy costs and increasing handset lifetime, through recycling programs, for example. The Third Generation Partnership Project (3GPP) Long Term Evolution (LTE) system has been chosen as the baseline technology for the research program; its specifications have recently been completed with a view to rolling out networks in the next two to three years [2].

The next section of this article discusses the architecture of existing base stations and identifies key parts of the system hardware where significant energy savings can be obtained.

BASE STATION POWER EFFICIENCY STUDIES

The overall efficiency of the base station, in terms of the power drawn from its supply in relation to its radio frequency (RF) power output, is governed by the power consumption of its various constituent parts, including the core radio devices.

Radio transceivers: The equipment for gener-

ating transmit signals to and decoding signals from mobile terminals.

Power amplifiers: These devices amplify the transmit signals from the transceiver to a high enough power level for transmission, typically around 5–10 W.

Transmit antennas: The antennas are responsible for physically radiating the signals, and are typically highly directional to deliver the signal to users without radiating the signal into the ground or sky.

Base stations also contain other ancillary equipment, providing facilities such as connection to the service provider's network and climate control. A major opportunity to achieve the power reduction targets of the program lies in developing techniques to improve the efficiency of base station hardware.

Analysis within the program has developed models for various base station configurations (macrocell, microcell, picocell, and femtocell) in order to establish how improvements in the hardware components will impact the overall base station efficiency. The starting point for this analysis has been the transmit chain. Near-market power consumption figures have been used in order to establish a benchmark efficiency against which improvements made as part of the project can be assessed. Target power consumption figures allow future overall base station efficiencies to be predicted.

REFERENCE BASE STATION ARCHITECTURE

The target system for the base station efficiency analysis is the LTE system with support for four transmit antennas. This system can exploit the space domain to achieve high data throughputs through multiple input multiple output (MIMO) techniques [2]. The reference architecture under investigation is shown in Fig. 2, this represents a macrocellular base station with three sectors, with an effective isotropic radiated power (EIRP) of 27 dBW per sector. The four transmit chains needed for the four antennas therefore require 12 power amplifiers (PAs) and antennas

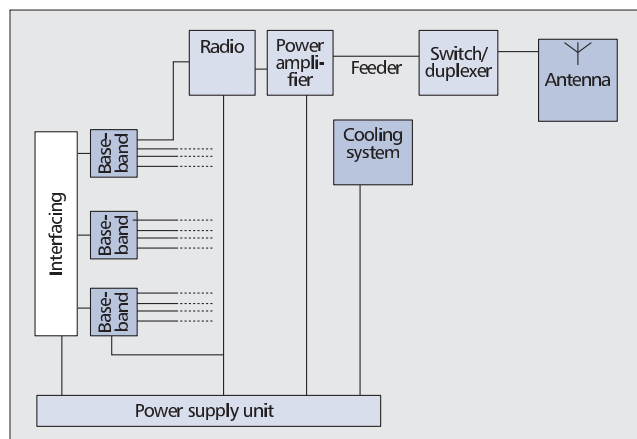


Figure 2. Reference base station architecture for a system with three sectors and four transmit antennas per sector for MIMO capability. For clarity only one transmit chain is shown.

per base station. For clarity, only one of the 12 transmit chains is shown in Fig. 2.

Estimated base station power consumption figures for the target system, reflecting the state of the art for the years 2010–2011, are given in Table 1. These estimates have been produced for reference purposes using efficiency figures from [3]; however, to reflect recent innovations [4], a power amplifier efficiency of 40 percent has been used. Two efficiency figures are calculated in Table 1: the top of cabinet (TOC) efficiency gives the ratio of the combined power output of the PAs to the power supply unit (PSU) power (which is used in studies such as [3]), and the radiated efficiency, which refers to the ratio of the efficiency to the total power radiated by the antenna. This second figure therefore includes antenna efficiency and feeder losses.

TARGET CONSUMPTION

The vision for the project is to specify an LTE compliant base station that is able to operate at much lower overall consumption, possibly sufficiently low to enable operation from renewable sources locally generated (e.g., solar or wind). Challenging power consumption targets have been set by the Green Radio program in order to achieve this aim; these target figures are given in the right column of Table 1.

The project target figures show an improvement in efficiency by reducing the power required to operate the base station by at least 50 percent. One solution reduces inefficiencies by locating the PA next to the antennas (typically both at the top of the mast) in order to minimize the power lost in feeder cables. This architecture also further reduces the need for cooling, which could arise were the PAs to be installed in cabinets in an equipment room. Additional efficiency gains are expected to come about by deactivating portions of hardware when unused.

Analysis shows that the greatest potential

for increasing the overall base station efficiency comes from improving the efficiency of the PA and antenna, as well as optimizing the power transfer between them. Work underway in the program is seeking to achieve efficiency figures of 85 and 90 percent for these components, respectively. In the case of the PA, one possible approach uses the Class J amplifier [5], which relies on fundamental and second harmonic tuning to achieve high efficiencies, while maintaining the linearity required for LTE operation. In the case of the antenna, the 90 percent efficiency target is to be achieved by exploiting highly efficient dual-polarized patch antenna elements.

CASE STUDIES FOR IMPROVING ENERGY EFFICIENCY IN WIRELESS BASE STATIONS

Earlier the power consumption of base stations was discussed and strategies to minimize power use in future base stations was described. In this section, we will move on to consider approaches which are designed around the signals that are transmitted by the base stations. In this case, the time dimension of these waveforms becomes important. In such a case, measures of energy (power \times time) rather than just power become important metrics to measure system performance effectively. This section will therefore begin by discussing suitable energy metrics and then move on to discuss three case studies, based around resource allocation, interference cancellation, and the use of multihop relaying strategies.

OVERVIEW OF ENERGY METRICS

The results in Fig. 1a of this article show the fact that base stations account for a significant proportion of the total power consumption of a wireless network. If new techniques are proposed to reduce the energy required in the network, it is important to provide meaningful metrics that identify what gains are achieved. The metrics to be used in the Green Radio project have been discussed extensively, and there are two particularly important metrics that are intended to be used during the project.

The first is an absolute measure of energy and is closely related to the industry concept of the energy consumption rating (ECR). This is typically defined as a ratio of peak power divided by the maximum data throughput for a base station transmitter. However, to be of practical use, the ECR should measure the consumed energy per information bit that is successfully transported over the network and is measured in units of joules per bit. This metric allows the absolute performance of different wireless networks to be calibrated. As a simple example, a typical LTE base station sector might operate over a bandwidth of 10 MHz with an average spectral efficiency of 1.5 b/s/Hz, thus achieving an average data rate of 15 Mb/s. If a base station antenna transmits 8 W of RF power (Table 1), the RF ECR value for this system would be 0.53 μ J/b. However, if the total power budget of the

Description	Power In (W)	Power Out (W)	Efficiency	Target Value
Radiated power (per sector)	8	501 (27dBW)	18dBi antenna gain	18dBi antenna gain
Antenna and Switch	12	8	65% efficient	85% efficient
Feeder	24	12	50% efficient	80% efficient
PA (total per sector)	60	24	40% efficient	85% efficient
PA (all sectors)	180	72		
Transceiver (all sectors)	180			70% reduction
Free Air Cooling	40			
Subtotal	400			
PSU Input	450	400	88% efficient	88% efficient
TOC Efficiency			16%	> 25%
Radiated Efficiency			5.3%	> 20%

Table 1. Estimated power consumption for base stations in 2010–2011 and target future power consumption values for base stations.

Resource allocation techniques that make the most efficient use of the RF amplifier have the potential to improve energy efficiency significantly. Such energy reductions could lead to further energy savings through switching off transceiver equipment and base station cooling.

base station (e.g., 450 W) is shared among 3 sectors (i.e., 150 W/sector) the ECR value for one sector would increase to 10 μ J/b.

The second metric is a relative measure rather than an absolute one and is more useful for comparing two different systems. Frequently, one may wish to compare the energy performance of a base station using a newly proposed technique (system under test) and compare to a baseline system where the approach is not deployed. The energy consumption gain (ECG) is simply the ratio (E_b/E_t), where E_b is the energy consumed by the baseline system and E_t is the energy for the system under test. The larger the value of the ECG, the more efficient the system under test becomes. However, as with the ECR metric, care needs to be taken to ensure that the energy calculations are performed in a fair manner. For example, if two base station designs are being compared, it should be ensured that both are serving the same number of users under the same traffic load conditions, in order to provide a fair comparison.

CASE STUDY 1: RESOURCE ALLOCATION STRATEGIES

RF amplifiers were identified as a key contributor to the overall energy consumption of a typical base station. In this article we use the term resource allocation to describe how the base station transmitter make the decision of how and when to transmit data to different users on the downlink (base-mobile link) within the cell it is serving. Resource allocation techniques that make the most efficient use of the RF amplifier have the potential to improve energy efficiency significantly. Such energy reductions could lead to further energy savings through switching off transceiver equipment and base station cooling.

In addition, analysis of data traffic in wireless networks show that the traffic load is typically very uneven across the cells. In the analysis of 200 cells in [2, Ch. 9], it is shown that even in peak hours, 90 percent of the data traffic is carried by only 40 percent of the cells in the network. Therefore, techniques that minimize energy consumption across varying traffic load conditions are an important research direction; here we describe two complementary techniques aimed at low and high traffic load conditions, respectively.

Under low traffic load conditions, the base station is likely to have more bandwidth available to transmit data to users than is actually required at that time. One frequency domain approach being studied in the project exploits spare bandwidth resources to reduce energy consumption. Due to the fact that channel capacity scales linearly with the available bandwidth but logarithmically with the radio transmission power, it is possible to trade spectral for energy efficiency, and achieve energy savings while retaining quality of service [6]. Rather than use a complex but spectrally efficient modulation scheme (e.g., 16-quadrature amplitude modulation [QAM]) with a narrow bandwidth, it is possible to use a simpler modulation scheme (e.g., quaternary phase shift keying [QPSK]) with a wider bandwidth.

Figure 3a shows predicted ECG gain results for this approach, as a function for the signal-to-interference-plus-noise ratio (SINR) required at the mobile receiver for a given data rate. Generally speaking, as the spectral efficiency of the data rate increases, so does the required SINR. The value of α specifies the permitted bandwidth expansion factor, and curves are shown for values of α in the range 2–6. For example, a bandwidth expansion of $\alpha = 2$ would permit 16-

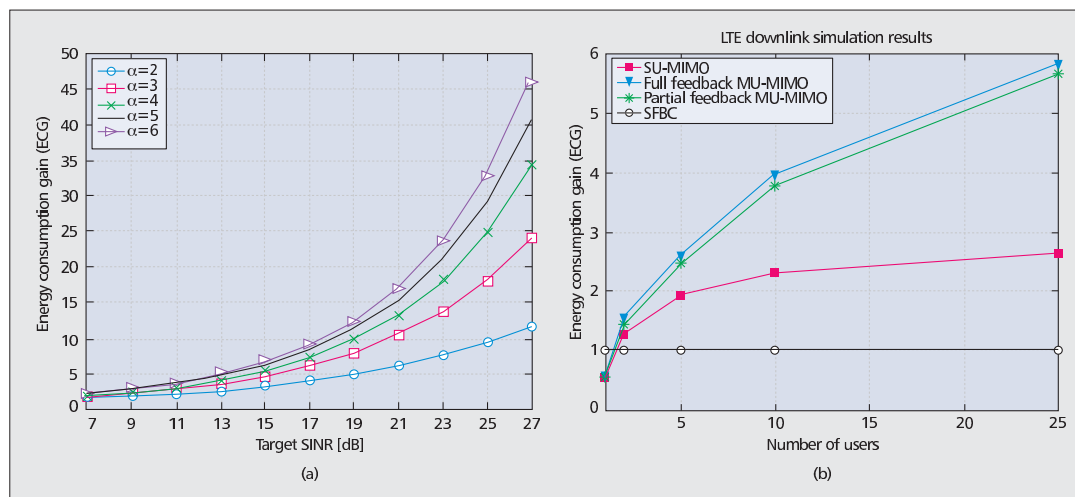


Figure 3. a) Simulated ECG of the frequency domain bandwidth expansion as a function of the required SINR at the receiver (after [5]); b) simulated ECG of various MIMO schemes, relative to SFBC all at 3 b/s/Hz spectral efficiency (after [6]).

QAM modulation (4 b/s/Hz maximum data rate) to be replaced by QPSK (2 b/s/Hz maximum data rate), which would require a lower SINR for reliable operation. The results show that as the SINR increases, so does the potential improvement in ECG from using the bandwidth expansion technique. Increasing the value of α beyond four is shown to provide diminishing returns in terms of ECG, except at very high values of SINR where very spectrally efficient modulation schemes would be used.

When the traffic load is high, the base station may be transmitting data to many users simultaneously, possibly using MIMO techniques. In this case, it is usually possible to exploit multi-user diversity to increase the overall multi-user capacity achieved via an opportunistic resource scheduling and allocation strategy. This is where the scheduler assigns resources according to the users' instantaneous channel conditions in the time, frequency, or/and space domains. The performance gains can be translated to further energy reduction at the transmitter. A link adaptation approach is also taken into consideration to ensure the most energy saving transmission mode is employed within the allocated resource for a required QoS level. As an example from [7], Fig. 3b shows the ECG performance of different MIMO precoding schemes compared to using the single-user MIMO diversity scheme space frequency block coding (SFBC) as the baseline case. The multi-user MIMO schemes exploiting a higher degree of diversity achieve lower cost in terms of required transmitter energy for each information bit. When the number of mobile users is large enough, performance evaluation results show that a fivefold energy gain can be achieved by multi-user MIMO through employing appropriate link adaptation and resource scheduling approaches compared to an SFBC system.

Future work in this area will study the best

combination of scheduling techniques from an energy efficiency perspective across the range of traffic loads experienced in future LTE networks.

CASE STUDY 2: INTERFERENCE MANAGEMENT AND MITIGATION

Interference cancellation schemes are indispensable to combat interference in any practical communication systems where multiple base stations share the same spectrum. The impact of interference is more severe as users move closer to the boundary region between two cells, leading to significant SINR and hence data rate reduction. Most existing interference cancellation schemes have been designed to increase the spectral efficiency and data rate, while overlooking energy efficiency. However, research efforts in the Green Radio program are focused on developing energy-efficient interference cancellation schemes. If the level of interference can be reduced at mobile terminals, it will permit base stations to reduce the wireless transmission energy without compromising the SINR of the wireless link. There are two complementary strategies being considered, as shown in Fig. 4a: distributed antenna systems and receiver interference cancellation.

One way to reduce interference in cellular systems is to coordinate the multiple antennas of the adjacent base stations to form a distributed antenna system (DAS) [8]. For the resulting coordinating DAS, each and every cell edge user is collaboratively served by all of its surrounding base stations rather than only by the single best base station. This permits the interference to users on the cell edge to be effectively controlled and mitigated by coordinated transmit beamforming at all of the participating base stations. The following three schemes can be used by coordinating downlink beamforming:

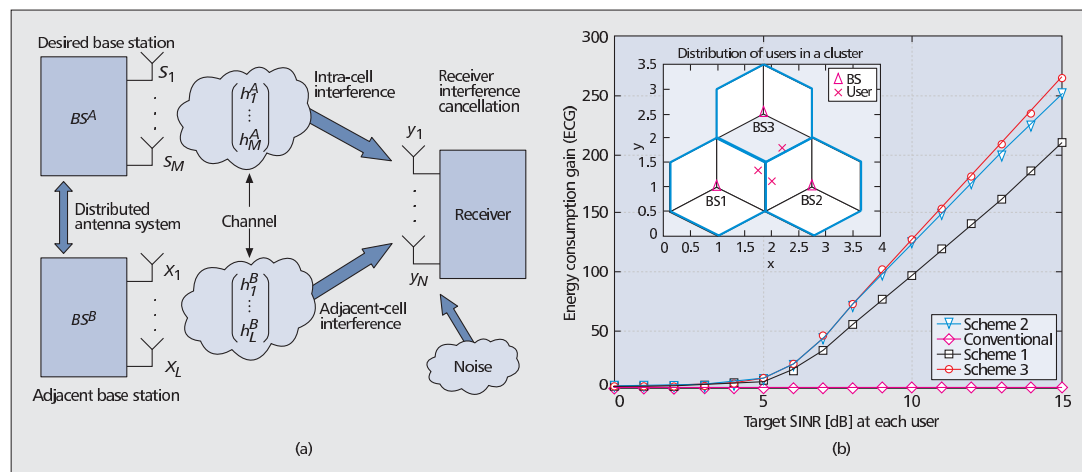


Figure 4. a) Example scenario for transmitter and/or receiver interference cancellation showing multiple base stations transmitting to a multiple antenna receiver; and b) performance comparison of three DAS schemes, plotting ECG (relative to no DAS case) vs SINR.

- The user is served by the base station providing the highest SINR while other base stations avoid transmitting signal energy toward that user.
- All users are served by multiple base stations using multiple antenna beamforming and coherent user-end combining (i.e., full exploitation of the interference suppression capability offered by the DAS).
- Users are allocated to one or more base stations based on their position.

These three schemes are compared in terms of ECG vs. SINR against the conventional non-cooperative case in Fig. 4b for a cluster of three cells with one user per cell. The results show that all three schemes significantly outperform the conventional system at high SINRs, with schemes 2 and 3 outperforming scheme 1. However, scheme 1 may be preferable over schemes 2/3 in practical implementation, since it requires much less channel data about the users to be exchanged between the base stations and hence less energy consumption.

An alternative scheme to DAS is to apply interference cancellation techniques at a multiple-antenna receiver. The performance of different algorithms has been compared in [9] for different numbers of transmitting antennas. Linear zero forcing (ZF) and minimum mean squared error (MMSE) techniques have been compared, along with nonlinear successive interference cancellation (SIC) variants of these methods. Generally, it is observed that more transmission energy is required as the number of transmit antennas increases. This is expected as intracell interference increases with the number of transmit antennas, resulting in higher transmission energy to maintain the same SINR.

In the absence of co-channel interference from neighboring base stations, it is observed that the MMSE weight optimization approach provides better transmission energy savings than the ZF approach at the desired BS; with the SIC

structure performing better than the linear receiver structure. This is because while the ZF criterion nulls out intracell interference but greatly amplifies adjacent-cell interference plus noise, the MMSE criterion jointly minimizes both intracell interference and noise, thus causing less severe amplification to the adjacent-cell interference and noise components. We also observe the same energy consumption trend when three adjacent base stations are present. The ECR values are around 3.4 times poorer than in the absence of co-channel interference for all receivers. This is because traditional interference cancellation (IC) techniques are often implemented at the link level (i.e., the point-to-point link between the desired BS and the receiver in this case). These link-level IC techniques are able to mitigate intracell interference but treat adjacent-cell interference simply as noise. More intelligent methods to cancel adjacent cell interference will be studied in future work, along with consideration of the most energy-efficient combination of IC techniques at both base stations and mobile terminals.

CASE STUDY 3: ENERGY-EFFICIENT ROUTING AND MULTIHOP

In a similar manner to the interference suppression techniques described above, the use of relays to exchange information between a base station and a mobile terminal may be an efficient way to improve base station energy efficiency. This is because the transmission distance can be reduced, increasing data rates or permitting reductions in transmission energy. Relays can enable important reductions of network energy consumption without complicated infrastructure modifications. These may be deployed in streets or buildings to provide improved signal quality to locations that might otherwise experience poor QoS.

In [10], the energy efficiency of several trans-

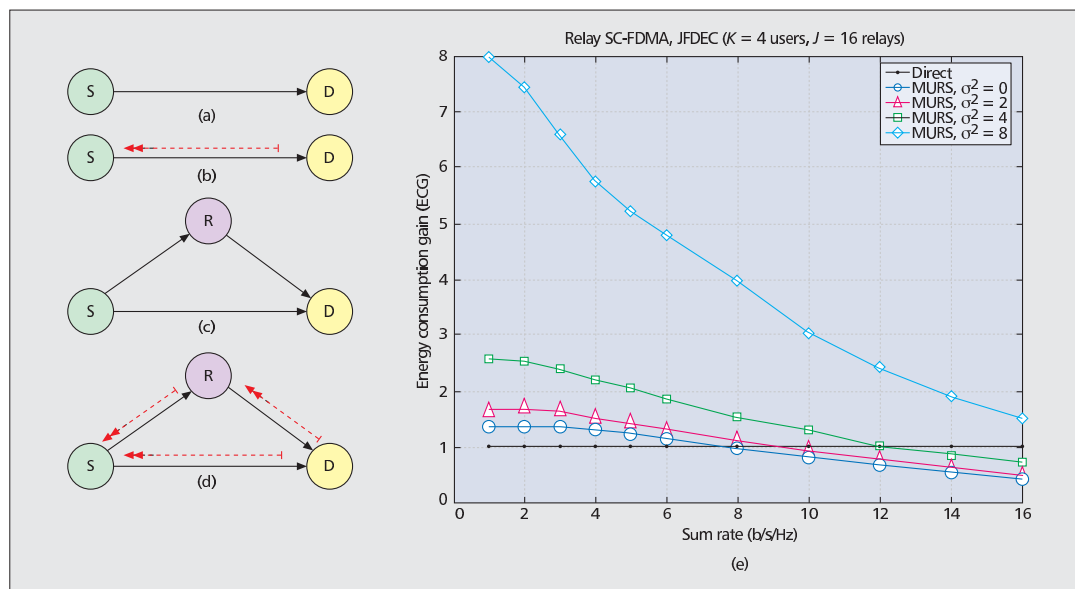


Figure 5. a) Direct wireless link with average channel knowledge; b) direct wireless link with instantaneous feedback of channel conditions; c) relay link with average channel knowledge; d) relay link with instantaneous feedback of channel conditions; e) performance gains of relay links after [11].

mission schemes shown in Figs. 5a–d are directly compared. Parts a and b show a conventional base station–mobile station link with average and instantaneous channel state feedback, respectively. Parts (c) and (d) show the case where a relay is present, again with average/instantaneous channel state feedback. It has been shown that the use of instantaneous channel feedback, which is the state of the art for resource allocation schemes, significantly reduces energy consumption compared to the case where only average channel state information is available. On the other hand, the impact of using a relay for communication is known to have a particularly strong impact for high signal-to-noise ratio (SNR) and low packet error rate conditions. This observation is in line with the basic conclusion from the literature that for fixed data rates, relaying is a particularly useful technique for high SNRs (or low packet error rates) because of the presence of the base station–relay–terminal path [11]; in this work, this conclusion is validated from an energy consumption perspective.

In [12], the energy efficiency of opportunistic cooperative relaying designed for the multi-user single-carrier frequency-division multiple access (SC-FDMA) uplink (mobile-to-base link) is investigated with the aid of a single-relay amplify-and-forward (AF) scheme. The AF relay estimates the received power of each subband and equalizes the power differences of the subbands, which corresponds to subband-based equalization. A joint frequency-domain equalization and combining (JFDEC) aided receiver is employed at the base station. In this scenario, there are 4 transmitting terminals and 16 available relays. The energy reduction of the

proposed design is a direct benefit of spatial, frequency and selection diversity. In contrast to [11], where no terrain effects, termed shadowing, were considered, they are included in these results. In this case, the shadowing variance becomes an important parameter and expresses the variability in the environment due to buildings and other large obstacles. It may be observed in Fig. 5e that if the SNR is relatively low, the proposed multi-user relay selection (MU-RS) aided cooperative system provides an ECG of up to 8 relative to the no-relay “direct” case when experiencing a shadowing variance of 0–8 dB. However, as the operating SNR increases to a relatively high value and the target data rate increases correspondingly, the benefits of invoking an MU-RS cooperative system erode. This is not unexpected, because sharing the total transmit power between the source and relay as well as the provision of two time slots results in a throughput loss, which is not fully compensated by the relaying gain attained. It is anticipated that similar performance results will be observed for the downlink case as well.

One important future target for the work in this area is to be able to compare the energy efficiency of relay techniques with the use of femtocells. Relays provide a connection to the Internet through the nearest wireless base station. Conversely, femtocells are small low-power base stations installed in the home or office that use a wired Internet connection to provide service. Understanding the full impact of the energy consumption of these differing forms of network connection is an important but challenging task for the Green Radio project.

CONCLUSIONS

This article has described the approach being taken in the Mobile VCE project to study novel approaches to reducing the energy consumption of wireless links, particularly in improving the design and operation of wireless base stations. Analysis has shown that when accounting for manufacturing or embodied energy costs, base stations have a much higher operational energy budget than mobile terminals. Proper modeling of the energy consumption of base stations has been shown to be an important issue when trying to obtain a clear view of how different radio technologies can reduce energy consumption. Three case studies of current research in resource allocation, interference suppression, and multihop routing have also been discussed. The means by which these methods can lead to energy savings have been described, and initial results that estimate the performance benefits of these techniques have been presented. The Green Radio project is a three-year program, which started in January 2009 and is starting to deliver initial results, some of which are described and discussed here. The project is being led by industry with the expectation that the most promising research outcomes can feed into future energy-efficient wireless standards and products.

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The Green Radio project is a three-year program, which started in January 2009 and is starting to deliver initial results. The project is being led by industry with the expectation that the most promising research outcomes can feed into future energy-efficient wireless standards and products.

approximately 100 papers published in international journals and conferences and 11 patents. The majority of the latter are now owned by industry.

PETER M. GRANT [F] is currently a senior professorial research fellow at the University of Edinburgh. He was in 2007 appointed to be the 8th Regius Professor of Engineering at the University of Edinburgh. In 2009 he was made an officer of the Order of the British Empire (OBE) in the Queen's birthday honors list. He holds fellowships of the IET, Royal Academy of Engineering, and Royal Society of Edinburgh.

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Energy-Efficient Scheduling and Bandwidth–Energy Efficiency Trade-Off with Low Load

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Abstract—This paper presents a novel adaptation of the score-based scheduling principle along with a method for trading-off bandwidth for energy efficiency for use in Long Term Evolution (LTE) systems. The score-based principle is adapted to make use of both a relative and absolute energy efficiency metric. This results in flexible energy efficient scheduling that preserves the quality of service (QoS), as well as reduces the interference in the system. The general principle behind bandwidth expansion is to extend a user’s bandwidth by a factor of α . The target throughput is maintained by switching to a lower order modulation scheme and adjusting any other link parameters as necessary. Through a theoretical derivation, it is established that the higher the user’s employed modulation order is, the greater the possible gains are from employing such a transmission mode. The calculated improvement in expended energy ranges from approximately 43% to 98%. Simulations are used to empirically validate the theoretical results. When an expansion of bandwidth by a factor of 2 is simulated, the bandwidth expansion mode (BEM) is more efficient in 93% of the time, and the expended energy is reduced by 44%, while improving on the QoS delivered by the benchmark system.

I. INTRODUCTION

Recently, energy efficiency in wireless networks has become a widely researched topic. This is due to the anticipated tenfold increase of traffic requirements in the next generation mobile networks and the costs associated with those, as well as the requirement for a significant reduction of the carbon footprint of such systems.

Energy-efficient scheduling is a topic that has been discussed widely within wireless sensor networks [1]. However, most of the work is in the context of trading transmission length for energy efficiency. Other current work is focused on joint efficient resource allocation and power control that minimize interference and maximize system capacity [2]. These works adopt overall network capacity as their measure of system performance. This assumption is in contrast with the goal of this paper, which is to introduce a novel scheduling mechanism that preserves system performance while minimizing the expended energy. Work by Meshkati *et al.* [3] has previously focused on trade-offs between throughput, delay, network capacity, and energy efficiency. In their work, Oyman *et al.* [4] explore the power-bandwidth trade-off in dense multi-antenna relay networks. However, their work is based on multi-antenna relay beam forming, and is primarily focused on enhancing spectral efficiency. Sinanović *et al.* [5] focus on the effect of power allocation on spectral efficiency in 2-

link decentralized networks. Their results are particularly interesting with regard to the effects interference has on spectral efficiency and hence energy efficiency. Omiyi *et al.* [6] propose a novel interference avoidance technique based on in-band signaling that apart from interference protection also achieves energy efficiency through significant reduction in interference. A good overview of energy efficient network protocols for wireless networks can be found in [7]. The concept of an energy efficient “sleep mode” has been investigated in [8]. This publication focuses on an on/off approach to sleep cycles in decentralized networks. Mobile stations (MSs) are allowed to turn off for periods of time depending on the traffic conditions. Recent work by Wang *et al.* [9] focuses on a more active approach, where energy is saved by cutting down on control signaling during low traffic periods.

This paper proposes a method for energy efficient resource allocation and an algorithm for trading bandwidth for energy efficiency during low load periods.

The rest of the paper is organized as follows. Section II introduces the concept behind trading bandwidth for energy efficiency. Section III provides a derivation of the gains warranted by the approach, as well as a rule that can be used to decide when to apply the principle. Section IV introduces an energy-efficient scheduling algorithm that enables the correct use of BEM. Section V presents the simulation platform used for empirical testing. The paper concludes with Section VI.

II. BANDWIDTH TRADE-OFF PRINCIPLE

The technique proposed in this paper is based on the fact that when usage is light and capacity is available, the user’s limited bandwidth can be increased by a factor of α , while the modulation order and signal-to-interference-plus-noise-ratio (SINR) requirement per frequency channel, Γ_i , are decreased. This results in a more power-efficient transmission. It is desired that the user’s currently achieved rate, R , is preserved. Hence, an energy saving can be incurred in a communications system without any degradation in service. This technique is henceforth referred to as BEM.

Consider the example frequency resource block (RB) allocation in Fig. 1. The user is allocated 4 out of a maximum 10 RBs. This presents the opportunity to allocate an additional 4 RBs, and switch to a more energy efficient lower order modulation scheme. An overall reduction in expended energy is hence achieved as derived in Section III. In a more general

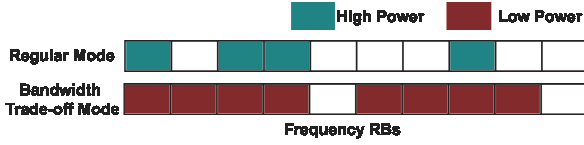


Fig. 1. Example frequency resource block allocation

scenario, a user can expand his bandwidth footprint by an integer factor of α , and, by making use of a look-up table, choose an appropriate modulation scheme, SINR target, and other required link parameters. The expansion factor has to be an integer since additional RBs are allocated.

The technique exploits the energy saving opportunity created through the fact that the transmission rate scales logarithmically with the achieved SINR, and linearly with the used bandwidth or number of channels.

III. THEORETICAL TREATMENT

A. Gain Derivation

The potential energy saving gains can be derived from Shannon's channel capacity:

$$C = B \log_2 \left(1 + \frac{S}{N+I} \right), \quad (1)$$

where B is the channel bandwidth, S is the total received signal power over the bandwidth, N is the total noise power, and I is the total interference power. In LTE systems, bandwidth is partitioned into RBs. Hence, (1) can be expressed as follows:

$$C_i = B_i \log_2 \left(1 + \frac{T_i G_{kj}}{N_0 B_i + I_i} \right), \quad (2)$$

where C_i is the capacity for RB with index i , B_i is the bandwidth of a RB, T_i is the transmission power of transmitter k on RB i , G_{kj} is the path gain between transmitter k and intended receiver j , N_0 is the noise power density, and I_i is the total interference power received in RB i . In the context of extending bandwidth, it might seem that the bandwidth and interference terms in the equation need to be scaled. When applying the technique proposed in this paper, there is no need to scale the $N_0 B_i$ or B_i term due to the way that an orthogonal frequency division multiple access (OFDMA) system functions. All operations are performed on a RB basis, the interference and noise that a RB experiences are not directly affected by allocating more RBs within the same cell site.

Ideally, the achieved SINR at RB i is greater than the SINR target, Γ_i :

$$\frac{S_i}{N_0 B_i + I_i} \geq \Gamma_i. \quad (3)$$

If this inequality is reduced to an equality, both energy efficiency and correct transmissions are ensured.

The first step is to calculate the BEM SINR target, Γ_i^{BEM} , from the regular SINR target, Γ_i . Let us assume that we would like to have the same overall transmission rate after more RBs are allocated, this yields:

$$\alpha (B_i \log_2(1 + \Gamma_i^{\text{BEM}})) = B_i \log_2(1 + \Gamma_i). \quad (4)$$

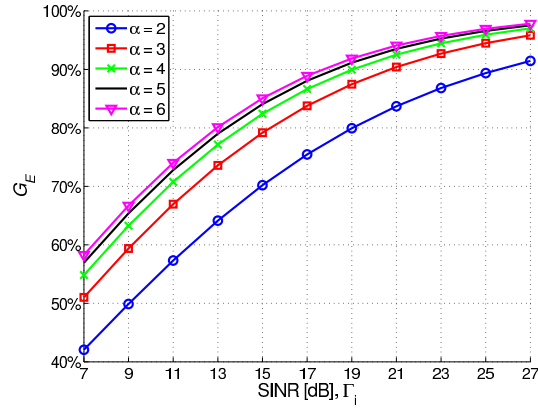


Fig. 2. Theoretical gain for BEM transmission

The above equation assumes perfect power control, as well as that the channel gains permit the required Γ_i to be achieved. After a simple manipulation, we arrive at:

$$(1 + \Gamma_i^{\text{BEM}})^\alpha = 1 + \Gamma_i. \quad (5)$$

Hence, Γ_i^{BEM} is the solution to (5). In the general case this is:

$$\Gamma_i^{\text{BEM}} = \sqrt[\alpha]{1 + \Gamma_i} - 1, \quad (6)$$

since all quantities are strictly positive. Let us assume that $A_i = (N_0 B_i + I_i)/G_{kj}$ is a constant. It is then possible to calculate the minimum transmission power for the desired SINR target, Γ_i :

$$T_i = A_i \Gamma_i. \quad (7)$$

By substituting (6) instead of Γ_i in (7), we can obtain the needed minimum transmission power in expanded bandwidth transmission mode, T_i^{BEM} :

$$T_i^{\text{BEM}} = A_i (\sqrt[\alpha]{1 + \Gamma_i} - 1). \quad (8)$$

Having done this, it is possible to calculate the gain in energy, G_E :

$$G_E = 1 - \frac{\alpha (\sqrt[\alpha]{1 + \Gamma_i} - 1)}{\Gamma_i}. \quad (9)$$

G_E can be regarded as a measure of how much energy, in terms of percentage or ratio, the newly proposed system saves over the original or reference system. The general principle behind it is:

$$G_E = 1 - \frac{E_{\text{new}}}{E_{\text{reference}}}. \quad (10)$$

This parameter is plotted in Fig. 2 for a number of different values for α and Γ_i . Higher Γ_i allows for larger savings in communication energy. The gain in expended energy ranges from approximately 43% to 98%. Expanding bandwidth grants a diminishing return in terms of energy reduction. This is visible in the increasingly close stacking of the curves as the value of α is increased. The behavior stems from the already derived G_E . BEM with $\alpha = 2, 3, 4$ seem to have the best trade-off between occupied bandwidth and energy efficiency. Trading up to $\alpha = 5, 6$ comes with a prohibitive decrease in bandwidth efficiency and practically no further gain in energy efficiency. For example, increasing α from 4 to 5 results in

additional 2 – 3% energy savings for a cost of an additional 25% used bandwidth.

B. Favorable Conditions

Another important aspect to consider is when is it advantageous to use BEM. Let us consider a standard 2-link scenario, where G_{11}^i and G_{22}^i denote the path gains for the desired links, and G_{12}^i and G_{21}^i are the path gains for the interfering links. The i superscript denotes that the channel is different for the different RBs due to frequency selective fading effects. Also, $G_{kj}^i = G_{kj} F_{kj}^i$, where G_{kj} is the path loss and F_{kj}^i is the frequency selective fading. Let us assume that only one transmitter-receiver pair at a time enters the energy efficient larger bandwidth mode. Moreover, once in BEM, the traffic is distributed equally over all RBs *i.e.* all Γ_i^{BEM} are the same. We would like to know when is it beneficial for a user to expand its bandwidth:

$$\sum_{i=1}^n T_i > \sum_{i=1}^{\alpha n} T_i^{\text{BEM}}, \quad (11)$$

where n is the total number of resource blocks per user in normal mode. Let us assume that $\alpha = 2$ and $n = 1$ for simplicity of presentation. Once the final answer is derived, it will be shown how to generalize it for any α . Let us express the transmission powers first:

$$T_i^1 = \frac{\Gamma_i}{G_{11}^i} (N_0 B_i + T_i^2 G_{21}^i), \quad (12)$$

where T_i^1 is the transmission power for Tx₁ on RB i , and T_i^2 is the transmission power of Tx₂ on channel i . For the energy-efficient transmission mode the above becomes:

$$T_i^{1,\text{BEM}} = \frac{\Gamma_i^{\text{BEM}}}{G_{11}^i} (N_0 B_i + T_i^2 G_{21}^i). \quad (13)$$

If channel conditions were the same across the different frequency resource blocks, equation (11) would always hold. However, that is not the case due to frequency selective fading. Let us re-write (11) for the particular α and n :

$$\frac{\Gamma_1}{G_{11}^1} (N_0 B_1 + T_1^2 G_{21}^1) > \sum_{i=1}^2 \frac{\Gamma_i^{\text{BEM}}}{G_{11}^i} (N_0 B_i + T_i^2 G_{21}^i). \quad (14)$$

After some manipulations, the general case when α and n take on any values, and we have multiple links the inequality becomes:

$$\sum_{l=1}^n \frac{\Gamma_l}{\Gamma_l^{\text{BEM}}} > \sum_{l=1}^n \left(1 + \sum_{i=(l-1)\alpha+1}^{l\alpha} \frac{F_{11}^l (N_0 B_i + I_i)}{F_{11}^i (N_0 B_l + I_l)} \right). \quad (15)$$

IV. ENERGY EFFICIENT SCORE BASED SCHEDULING

BEM requires a scheduler that ensures that the rule in (15) is fulfilled before allowing MSs to enter BEM. RBs that are expensive in terms of expended energy should not be allocated. Also, to maximize the benefit from expanding bandwidth, it is necessary to choose the RBs with the best channel conditions as they are most energy efficient. Moreover, the overall system

efficiency needs to be considered while allocating resources, not only the performance experienced by a particular user.

The above can be achieved by adapting the score based scheduling principle [10] to use an energy efficiency metric, as well as tailoring the allocation sequence and conflict resolution to promote both fairness and energy efficiency. This scheduler will henceforth be referred to as energy efficient score based scheduler (EESBS).

The allocation routine starts by using a score-based scheduler that relies on channel gains, interference characteristics and an energy metric to find the most energy-efficient RBs to transmit on. It is based on the following equation:

$$s_i^k(t) = 1 + \sum_{j=1, j \neq i}^W \mathbb{I}_{E_i^k(t) > E_j^k(t)} + f^k(m), \quad (16)$$

where $s_i^k(t)$ is the score for RB i at time t for user k , W is the total number of RBs available for allocation to the user at the time, $E_i^k(t)$ is the energy metric for RB i at time t and user k , and $f^k(m)$ is a penalty function for user k . Lower RB scores mean a RB is more likely to be allocated. The penalty function is used to further promote fairness in the system, as well as to provide convenient means to control the resource distribution. This function can also be tailored to specific requirements. One can envision penalty functions that mimic the behavior of already popular schedulers like proportional fair *etc.*. The energy metric can be any measure that assesses the energy performance in a way that conforms to (15). RBs that cannot achieve the required minimum signal-to-interference-and-noise ratio (SINR) are given a score of infinity and are hence not allocated. Conflicts between users are resolved by calculating the energy efficiency scores for all users, and allocating the conflicting RBs to the users who can use them most efficiently. The rest of the conflicting users are allocated their next best resource.

The procedure is repeated until the user rate constraints within the base station (BS) are satisfied, or it is found that it is impossible to do so. The operation of the scheduler is covered in more detail in pseudo code in Algorithm 1.

V. SIMULATION RESULTS

An LTE based simulator is developed to evaluate the performance of the proposed transmission mode. Within the simulator platform two proposed systems – one with EESBS, and another with EESBS coupled with BEM, are compared to a system that uses round robin (RR) scheduling. The benchmark system is identical to the proposed systems except for the lack of bandwidth trade-off capability and energy efficient scheduling algorithm.

A. Simulation System and Scenario

The system scenario of choice is a cellular system. A central cell with two tiered wrap-around deployment is used. Only the central cell is considered when results are collected to avoid edge effects. This also helps avoid any unrealistic transient effects caused or due to the proposed techniques. The channel model used is the LTE urban micro-cell (UMi) [11] as defined in Table I, where d is the distance between transmitter and receiver, f_c is the carrier frequency in MHz, h_{BS} is the

Algorithm 1 : Amended score-based scheduler

```

INITIALIZE the number of required RBs for each user
while Users require RBs do
  CALCULATE scores for all users based on the energy
  metric and score equation
  for  $i = 1$  to number of BSs do
    FIND this BS's users' best RBs
    if User's best RB is not allocated AND is usable AND
    is not another user's best RB then
      ALLOCATE RB to user
    end if
    if There were conflicting RBs between users then
      RESOLVE conflicts by allocating RB to most effi-
      cient user, and next best RBs to the remaining users
    end if
  end for
  if There are no available RBs for allocation OR no users
  require more RBs then
    EXIT while loop
  end if
end while

```

TABLE I
CHANNEL MODEL

	Path Loss [dB]	St. dev. [dB]
LOS	$L = 22 \log_{10}(d) + 28 + \log_{10}(f_c)$	$\sigma = 3$
	$L = 40 \log_{10}(d) + 7.8 - 18 \log_{10}(h_{BS} - 1) - 18 \log_{10}(h_{UT} - 1) + 2 \log_{10}(f_c)$	$\sigma = 3$
NLOS	$L = 36.7 \log_{10}(d) + 22.7 + 26 \log_{10}(f_c)$	$\sigma = 4$

elevation of the base station (BS) antenna, and h_{UT} is the elevation of the user terminal antenna. In practice one of the three path loss equations is selected, based on d .

The probability of line of sight (LOS) is given by:

$$\Pr_{LOS} = \min(18/d, 1)(1 - \exp(-d/36)) + \exp(-d/36) \quad (17)$$

A power control algorithm is necessary to ensure that the minimum feasible transmission powers can be calculated, so that the proposed techniques can be correctly evaluated. The system employs the Foschini-Miljanic simple power control algorithm. It is based on the following control equation [12]:

$$T_i^k(t) = \frac{\Gamma_i}{\gamma_i(t-1)} T_i(t-1), \quad (18)$$

where $T_i^k(t)$ is the transmission power used for user k on RB i for time instance t , and $\gamma_i(t-1)$ is the achieved SINR at the previous time instance. Results are obtained in the steady state *i.e.* the transmission power vector is given a sufficient number of power control loop iterations to converge.

All users use the same two modulation schemes – one for transmissions in normal mode, and one for transmissions in BEM.

A constant rate per user traffic model is used to make sure that all users contend for transmission. All users are assigned the same required rate.

The downlink transmission direction is simulated. Data is collected from one time slot after the system has settled to a stable resource allocation. Each user is assumed to require a set

TABLE II
SYSTEM PARAMETERS

Parameter	Value
Total Bandwidth	18 MHz
Carrier Frequency	2.14 GHz
Resource Bandwidth	180 kHz
Number of Resource Blocks (RBs)	100
Subcarriers per RB	8
Noise Floor	-121.42 dBm
BS Maximum Power	43 dBm
User Speed	3 km/h
SINR targets, Γ_i	3, 7 dB
Data rates	1, 2 bits/symbol
Users per BS	20
Resources per User, x	3, 6
Inter-site distance	300 m
Bandwidth expansion factor, α	2

number of frequency resource blocks in normal, benchmark, mode. RBs that cannot be used for transmission due to poor channel conditions are not considered during the process. The BEM system requires a RB allocation as a starting point to its operation. It makes use of the resulting EESBS allocation and optimizes it.

The simulator assumes use of existing digital modulation schemes that are based on constellations with size 2^q . As a result, the rate of transmission in terms of bits per symbol is also a power of two. Since we would like to preserve the transmission rate that was incident before the allocation of additional RBs in BEM without dynamically changing the time length of transmitted symbols, the following equation is in effect:

$$R_i = \alpha R_i^{\text{BEM}}, \quad (19)$$

where R_i is the achieved rate on RB i prior to allocating additional resources, and R_i^{BEM} is the new desired rate per RB after allocating the additional $\alpha - 1$ RBs. It follows from both R_i and R_i^{BEM} being of the form 2^q that α also needs to be of the same form. It is possible to use almost any other integer value for α , if other link parameters are also changed, for example coding rate.

The penalty function used within the scheduler is $f^k(m) = m$, where m is the number of currently allocated RBs to a user. This means that the more RBs are allocated to a user, the larger the penalty resulting in a fair allocation. The scheduler also chooses whether to allocate resources based on their effect on the overall energy efficiency in BEM. If the allocation of a particular RB affects negatively the overall efficiency of the BS, it is not allocated.

Two parameters are used to evaluate the performance of the three systems – energy consumption gain (ECG) and data rate.

ECG is a comparison between two systems where E_1 is taken as the reference system, and E_2 is the proposed one. It is calculated as:

$$\text{ECG} = \frac{E_1}{E_2}. \quad (20)$$

All LTE system parameters are listed in Table II.

B. Results

Simulations are performed for $\alpha = 2$. This particular value is chosen as it theoretically offers the best cost-benefit value. A system load of 60% is assumed. This results in a desired target rate of 1.08 Mbps per user. It represents a possible threshold

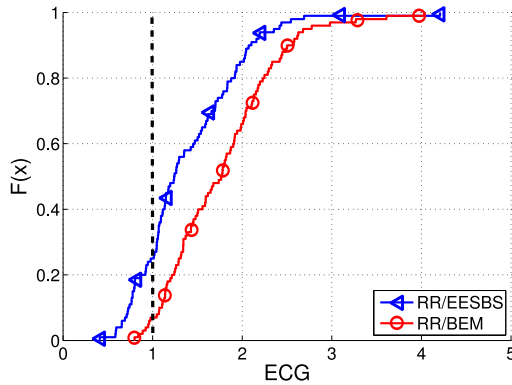


Fig. 3. Energy consumption gain CDF

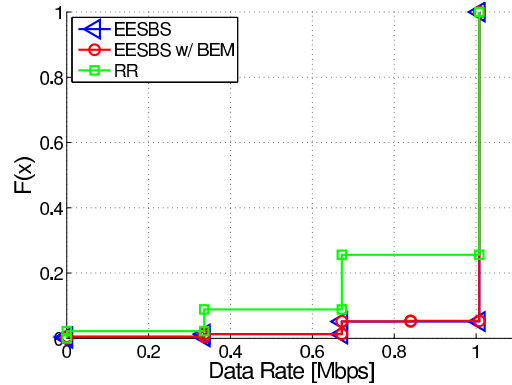


Fig. 4. Data rate CDF

when considering whether the system is lightly loaded or not. If a lower value is used, the results remain approximately the same. Gains decrease with the increase of traffic loading as resources are not enough to allow all users to switch to the proposed energy-efficient transmission mode.

The simulated ECG curve for the two systems can be found in Fig. 3. In 75% of the time, the EESBS system is more efficient than the benchmark. On average, it uses 1.25 times less energy. The BEM system is better in 93% of the time, using 1.77 times less energy on average. The data rate per BS can be found in Fig. 4. At the 50th percentile, all the systems achieve the same data rate per user. The two proposed systems perform, almost identically. They outperform the round robin benchmark for 25.6% of the time by providing higher throughput. The quantum jumps in data rate are due to the on/off nature of the RBs – they can either be used successfully or not be used at all. Since the simulation is performed with 3 required RBs per user, there are three jumps in probability in the cdf.

VI. CONCLUSION

An investigation of an energy efficient transmission mode is introduced. The proposed scheduler together with the energy efficient bandwidth expansion technique achieve significant energy savings in more than 93% of the random simulation realisations. On average, about 44% of the expended energy is saved. This is done during low loading periods, and at no expense to the target data rates that users are experiencing at

the time. The savings scale with square root of the original user SINR target, hence higher order modulation transmissions stand to gain more than lower order ones. Also, it is demonstrated that trading further bandwidth for energy comes with diminishing returns. As more bandwidth is utilised, the benefit from it decreases. The technique promises very significant energy savings when light overnight load factors are present.

VII. ACKNOWLEDGMENT

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Resource allocation for energy efficient cellular systems

Stefan Videv*, John S Thompson, Harald Haas and Peter M Grant

Abstract

The need for more throughput in wireless cellular networks has been increasing in recent years. It has led to an increase in operational costs due to higher energy use as operators deploy more cell sites or increase transmission power at existing ones to satisfy demand. Energy costs are a major expense, and reducing them is a priority. This article presents a scheduler which aims to solve the problem of energy efficient resource allocation in orthogonal frequency division multiple access (OFDMA) cellular systems. The suggested approach is to make the resource scheduling process also consider energy costs as well as allow it to manipulate these by exploiting time/frequency vs energy efficiency trade-offs that are present in the system. The energy efficient score-based scheduler (EESBS) is a novel scheduler which takes energy costs into account when allocating resource blocks (RBs) to users. This allows it to promote energy efficiency in the system alongside throughput and fairness maximization. One of the means it has to manipulate users' expended energy is the bandwidth expanded mode (BEM). BEM is a technique that allows the scheduler to decrease a user's energy consumption by allocating it more RBs and maintaining a constant data rate. This is possible when the energy consumption is dominated by the energy used for data communication as opposed to control channel overhead transmission. Time compression mode (TCoM) is a technique that is complementary to BEM. It allows for energy savings through a reduction of the number of allocated RBs to a user when the energy consumption is dominated by the transmission of signaling traffic. Both BEM and TCoM need to be employed by an energy-aware scheduler like EESBS in order to extract the maximum performance gains. A realistic framework modeling future cellular systems is established to test the performance of the proposed techniques. Within this framework, EESBS generates an average energy saving of 29% over a frequency selective proportional fair (FsPF) benchmark. EESBS coupled with BEM or TCoM achieves a saving of 38% over the same benchmark. These savings are achieved with no detriment to user satisfaction in terms of achieved data rate.

1. Introduction

Wireless cellular communications have seen rapid development in recent years. With the advent of the smart phone, the desire for higher data rates has grown rapidly. It is commonly accepted that the increase is exponential with time [1]. From an operator's point of view, this is not desirable, as revenue has been increasing at a linear rate at best. This has resulted in a drive to reduce the operational costs associated with wireless cellular networks. Base stations' (BSs) energy consumption is one of the main contributors to the aforementioned cost. There has not been any significant coordinated attempt to optimize BSs energy

performance in the past. Also, heightened environmental awareness has emerged as an additional incentive to minimize operational impact. All these factors have led to several initiatives which target a reduction of the energy consumption of wireless cellular networks by between 10 to 100 times through future research—for example, the mobile Virtual Center of Excellence's Green Radio project [2], the EARTH project [3], Greenet [4], and recently GreenTouch.

As a result, research has emerged on the topic of energy-efficient scheduling. This topic has previously been discussed widely in wireless sensor networks [5,6]. However, most of the work is in the context of relaxing quality of service constraints for energy efficiency. Within the traditional multi cell literature, the main topic of research is achieving higher spectral efficiency

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with an additional emphasis on fairness among users [7]. The focus is moving to increasing the energy efficiency of BSs towards that of mobile terminals. Han et al. [8] compare several schedulers in terms of throughput, fairness and energy efficiency. Their proposed fair cluster algorithm is focused on providing fairness over the user population but is also able to deliver energy efficiency improvements of about 12% compared to a round robin (RR) benchmark. The other proposed greedy algorithm, provides a 10-fold reduction in used energy, unfortunately at the expense of a detrimental reduction in both throughput and power fairness as measured by an adaptation of Jain's fairness index. Yao and Giannakis [6] have proposed an energy efficient scheduling algorithm based on non-uniform time division multiple access (TDMA) that varies transmission length based on channel state and the size of the transmitted information. Their scheduler is able to achieve a reduction in used energy of up to 80% at the cost of longer transmission times. Interference mitigation is another of the key means to improve energy efficiency. Recently, interference mitigation techniques have been adapted to work in systems that employ multiple-input and multiple-output (MIMO) transmissions [9,10]. Another important topic is sleep modes [11-13]. These traditionally allow the system to actively alter its energy consumption by turning on and off its radio frequency (RF) front end depending on traffic conditions and transmission requests. Recent work by Wang et al. [14] focuses on pooling together under-loaded time slots (TSs), so that unused ones can be switched off. This allows for an interactive sleep mode that is able to respond to network and user demands in a better way. Significant gains of up to 90% are achieved for very low load factors. Gains are possible as long as the load factor is less than 60%. As femto-cells are slowly being rolled out, research into optimum BS deployment is moving in the direction of optimizing for energy efficiency and not only coverage and delivered throughput [15]. However, the gains from deploying femto cells are strongly dependent on the particular scenario of use.

This article presents a novel scheduler, the energy efficient score-based scheduler (EESBS), and two novel techniques that are able to manipulate energy expenditure through resource scheduling, bandwidth expansion mode (BEM) and time compression mode (TCoM), that work together to reduce energy consumption in a wireless cellular system. The novelty of the three techniques lies in the scheduler being energy aware, and having the ability to use BEM or TCoM when it is beneficial to the system in terms of energy consumption. This is done without loss in other performance parameters.

The rest of the article is organized as follows. Section 2 introduces EESBS. This is followed by a short

overview of BEM in Section 3, and theoretical derivations on its performance. Next TCoM is introduced along with a derivation of its performance. Simulation set-up and empirical results are presented in Section 5. The article concludes with Section 6.

2. Energy efficient scheduling

A major component of any energy efficient wireless communication system is the resource scheduler. A well designed system needs to be aware of the energy costs that different resource allocation decisions entail. This awareness allows the system to integrate any performance enhancements simply as alternative allocation options available to reduce energy consumption while satisfying users' demands.

2.1. Score based scheduling

The concept of a score based scheduler is proposed in [16]. In a TDMA-like system, a user $i(t)$ with the best score is selected at slot t to transmit:

$$i(t) = \underset{j=1,\dots,U}{\operatorname{argmin}} s_j(t), \quad (1)$$

where U is the total number of users in the system, $s_j(t)$ is the score of user j at slot t , which corresponds to the rank of his current transmission rate $r_j(t)$ within the already observed values $r_j(t)$, $r_j(t-1)$, ..., $r_j(t-W+1)$ with W being the window size in time. When there are two users with the same score, one is chosen at random. Formally, the scores are calculated as follows:

$$s_i(t) = 1 + \sum_{l=1}^{w-1} \mathbb{1}_{\{r_i(t) < r_i(t-l)\}} + \sum_{l=1}^{w-1} \mathbb{1}_{\{r_i(t)=r_i(t-l)\}} X_l, \quad (2)$$

where $\mathbb{1}$ is the indicator function which returns 1 if the condition in the brackets is true and 0 otherwise and X_l 's are independent identically distributed random variables that take on value from $\{0, 1\}$ with $\Pr(X_l = 0) = 1/2$.

Score based scheduling evaluates each user's performance on a future TS relative to their past experience, and assigns the aforementioned TS to the user who can benefit the most relative to their history.

2.2. Energy efficient score based scheduler (EESBS)

The score based scheduler in its basic form outlined above cannot be used to enhance energy efficiency while not compromising fairness and delivered data rate. The metric used for rating the resources needs to be changed, as well as the whole approach being adapted to OFDMA rather than TDMA systems. Resource allocation needs to be done and updated at a regular period to keep up with the channel conditions—for example every long term evolution (LTE) sub frame. In general,

the shorter the time span for which resources are allocated, the better the energy efficiency would be. This is due to less time being allowed for the channel conditions to change.

To promote energy efficiency, RBs that can be used in a highly energy efficient manner need to be allocated first. The use of a metric for rating them that measures the energy efficiency of the RB can achieve the desired result. A large number of metrics can be used—total energy used, energy per bit delivered etc. In this work, total RF transmission power is used. A RB's energy performance is compared to that of the remaining RBs available for allocation to that user, and scores are assigned. Moreover, when a conflict between users arises—the user who can use the RB most efficiently among the contending users is allowed to transmit using it. The rest of the users are allocated their next best RB.

Also, fairness among users has to be assured while satisfying each user's data rate requirement as best as possible. To ensure that, users are allocated one RB at a time until their service requirements are met. By doing so, the effect that high demand users have on low demand ones is minimized. The total number of users in the system becomes more important rather than the existence of high demand users assuming all users are given the same priority. Please note the distinction between high priority and high demand users. High priority users will always have a detrimental effect on fairness in the system.

The equation for calculating scores hence becomes:

$$s_q^j(t) = 1 + \sum_{k=1, k \neq q}^M \mathbb{1}_{E_k^j(t) > E_q^j(t)} + f^j(m_j), \quad (3)$$

where $s_q^j(t)$ is the score for RB q for user j at TS t , $E_k^j(t)$ is the energy metric evaluated for user j on RB k at t , M is the total number of RBs and $f^j(m_j)$ is a penalty function based on the number of already allocated RBs for the user. Lower scores indicate more desirable RBs. The energy metric and penalty function used within this work are defined as $E_k^j(t) = P_k^j(t)$, where $P_k^j(t)$ is the RF transmission power required on RB k for user j , and $f^j(m_j) = m_j$, respectively. It is in theory possible to assign each user a separate penalty function, as well as to have a penalty function that prioritizes users based on different criteria, such as vulnerability, subscription plan etc. This makes EESBS a versatile and easy to tailor scheduling technique.

A pseudo code implementation of the score based scheduler can be found in Algorithm 1. The **RESOLVE** clause represents the process through which conflicts between users are resolved. A conflicting RB is allocated

to the user who needs the least amount of energy to use it, whereas the rest of the users are allocated their next best RB according to the calculated scores.

Algorithm 1. Amended score-based scheduler

```

INITIALIZE requiredResources(1 ... j) ← calculate
number of required RBs for all users
while sum(requiredResources) > 0 do
  CALCULATE  $s_q^j(t) = 1 + \sum_{k=1, k \neq q}^M \mathbb{1}_{E_k^j(t) > E_q^j(t)} + f^j(m_j)$ 
for all users and RBs
  for i = 1 to number of BSs do
    FIND best RB for each user connected to this BS
based on  $s_q^j(t)$ 
    if User's best RB is not allocated AND is usable
AND is not another user's best RB
    then
      ALLOCATE RB to user
    end if
    if There were conflicting RBs between users then
      RESOLVE conflicts by allocating RB to most
efficient or priority user
      ALLOCATE next best RBs, based on  $s_q^j(t)$ , to
the remaining users
    end if
  end for
  if There are no available RBs for allocation then
    EXIT while loop
  end if
end while

```

RUN power control algorithm

The last step in the scheduling algorithm is to run a power control subroutine. Power control is necessary to ensure that the minimum feasible transmission powers can be calculated, which allows the proposed techniques to be correctly evaluated. This ensures the most efficient operation of the system. The algorithm of choice here is the Foschini-Miljanic [17] power control algorithm due to its simplicity and low computational overhead. It is based on the following iterative control equation:

$$P_q^j(t) = \frac{\Gamma_q}{\gamma_q^j(t-1)} P_q^j(t-1), \quad (4)$$

where $P_q^j(t)$ is the transmission power used for user j on RB q for TS t , Γ_q is the SINR target for RB q , and $\gamma_q^j(t-1)$ is the achieved SINR at the time instance prior to allocating resources. The power control subroutine should be allowed to run until the difference in the transmission power vectors between iterations, ε , has converged. Within this work, ε is defined to be 1% of the maximum BS RF transmission power. This is reflected in a relatively low number of control loop iterations required—on average 6-7. The transmission

powers used to calculate the energy efficiency metric used for allocation will be different from the ones actually used for transmission. This will result in a difference in the energy efficiency expected at allocation and the achieved one. Since the problem of energy efficient allocation of RBs and power to transmit on them is NP hard, this article presents a heuristic solution. Within this framework, each allocation iteration improves on the energy efficiency of the system.

3. Bandwidth expansion mode

3.1. General description

There are times in the operation of any cellular wireless network when there are only a few users who may demand high transmission rates—for example early in the morning or in rural area cell sites. It is reasonable to assume that at those times unused bandwidth should be available in cells operated under a LTE system. It is hence advantageous to employ techniques/algorithms that trade-off unused bandwidth for energy efficiency.

BEM [18] operates by allowing a user to expand his limited bandwidth by an integer factor of α while preserving the already achieved data rate. The allocated bandwidth is increased while the modulation order and signal-to-interference-plus-noise-ratio (SINR) requirement per frequency channel, Γ_q , are decreased to maintain the communication rate. The technique exploits the energy saving opportunity created through the fact that the transmission rate scales logarithmically with the achieved SINR, and linearly with the used bandwidth or number of channels. Hence, an energy saving can be incurred in a communications system without any degradation in service. Moreover, robustness of communication is increased as data is transmitted over more channels or RBs.

Consider the following example frequency RB allocation. A user is allocated 4 out of a maximum 10 RBs and transmits on them with relatively high power. This presents the opportunity to allocate an additional 4 RBs, and switch to a lower order modulation scheme if possible. An overall reduction in expended energy can be hence achieved. For example, doubling the used bandwidth and going from 16-QAM to 4-QAM increases the energy consumption by a factor of two, but at the same time reduces it by 3.16 times due to the more efficient modulation which results in a net reduction of 1.58 times. In a more general scenario, a user can expand his bandwidth footprint by a factor of α that is a real number by choosing an appropriate modulation scheme, SINR target, coding scheme and other required link parameters. However, it must be stressed that only an integer number of RBs can be allocated to each user. The integer constraint on α is imposed within this work for simplicity.

The reduction in energy due to BEM can be calculated in the form of energy consumption gain (ECG) as:

$$ECG_{BEM}^{RF} = \frac{E_{ref}}{E_{new}} = \frac{\Gamma_q}{\alpha (\sqrt[1]{1 + \Gamma_q} - 1)}, \quad (5)$$

where E_{new} is the energy required for operation by the investigated system, E_{ref} the energy for the reference system, α is the bandwidth expansion factor, and Γ_q is the required SINR on the link prior to expanding the bandwidth. Also, the RF superscript stands for radio frequency, as the expression above takes into account only the radiated RF energy used for data transmission. The expression is derived starting from Shannon's capacity equation—the rate for the system with BEM is equated to that to the reference system without BEM, and the BEM SINR target is computed as a function of the original one. The energy consumption of BEM and the reference system are then calculated to arrive at the ECG expression.

3.2. Effect of control channel overhead

Allocating additional resources raises the question of what happens to the control channel overhead. This needs to be answered in order to correctly assess the gains from BEM. Hence, the behavior of control overhead transmissions needs to be modeled and included in the analysis. Typically, cellular systems have a broadcast channel which carries information that allows the other channels in the system to be configured and used for communication. The 3rd Generation Partnership Project (3GPP) LTE makes use of a Physical Broadcast Channel (PBCH) which carries a 'Master Information Block' (MIB), as well as a Physical Downlink Control Channel (PDCCH). Both are a part of the Physical Downlink Shared Channel (PDSCH)—they are allocated particular resources in time and frequency [19].

We assume that the PBCH, reference, and synchronization signals are transmitted with a constant power, so that they can achieve coverage of the complete intended cell site. PBCH information is transmitted every 40 ms or every 40 sub-frames. In addition to that, in every sub-frame there is PDCCH data as well as reference signals that are transmitted. The PDCCH data can be configured to occupy the first 1, 2, or 3 OFDM symbols.

If we are to quantify the total overhead due to PBCH and PDCCH using the values presented above, we calculate that it varies between approximately 12.9 and 26.9%. It is important to note that this is overhead both in terms of communication time and energy. The contribution of PBCH is relatively minor—approximately 1.3% relative to the complete system. Of course, there are also other types of overhead that are not considered here—for example Physical Control Format Indicator

Channel (PCFICH) and Physical Hybrid ARQ Indicator Channel (PHICH). These do not constitute a significant part of the control channel overhead in the system. It is also important to note that the PDCCH could be turned off if the particular frequency resource blocks (RBs) are not going to be used, whereas the PBCH cannot be turned off as it is required so that new users can connect to the network. Hence, only the overhead from the PDCCH will be considered in this article.

The following assumptions are made throughout this work. The PDCCH along with the reference signals can be turned off if the particular RB is not in use until the next allocation cycle. This means that the control channel overhead due to PDCCH can be modeled as a transmission that occupies a fraction of the TS at a constant pre-set RF power.

Allocating more resources to users by allowing them to enter BEM means that there will be an additional control channel overhead associated with these which will affect the overall energy use. It is important to model this so that the real-world performance of this technique can be better assessed.

The ECG expression for BEM needs a significant alteration to account for the effect of a constant power

control transmission. After simplification, the new ECG expression for transmitter k and intended receiver j becomes:

$$ECG_{BEM}^{CC} = \frac{\sum_{q=1}^n (1 - \phi) \frac{\Gamma_q(N+I_q)}{G_{kj}^q} + \phi P_{ref}}{\sum_{q=1}^n (1 - \phi) \frac{(\frac{q}{\sqrt{1+\Gamma_q}} - 1)(N+I_q)}{G_{kj}^q} + \phi P_{ref}}, \quad (6)$$

where n is the total number of RBs allocated, N is the noise floor, I_q is the interference received on RB q , G_{kj}^q is the path gain for RB q , ϕ is the fractional control channel overhead, and P_{ref} is the power with which the reference signals are transmitted.

The new Equation, (6), is plotted for an example single carrier system with $\alpha = 2$ and $\phi = 0.15$ in Figure 1 where RF output power refers to the power radiated from a BS antenna in the system.

Control channel overhead introduces new patterns in the gain behavior for BEM. There is a variation in the gain experienced depending on the ratio between the data and the control channel transmission power. The higher the ratio, the closer to the previously calculated theoretical gains the system performs as the effect of

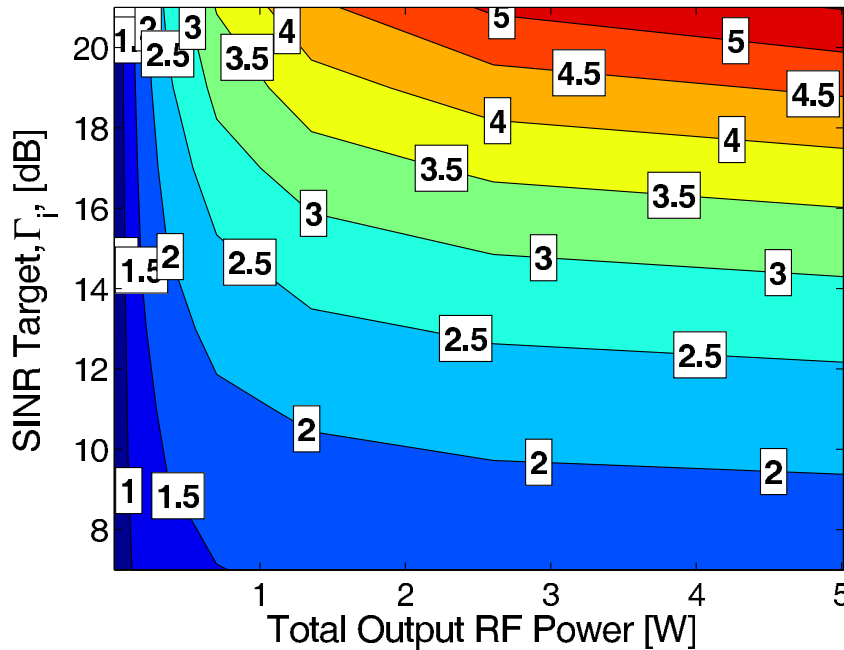


Figure 1 ECG for BEM with control channel overhead ($\phi = 0.15$ and $\alpha = 2$).

control transmission overhead becomes negligible. For low values of this ratio, the energy consumption of a communication node is dominated by the control channel overhead. In that case, increasing the number of RBs that are in use compromises the energy efficiency making the use of BEM not desirable. Having a higher initial SINR target before employing BEM results in larger gains from the technique as already established.

3.3. Effect of hardware operational efficiency

Switching the operation of a BS from one output RF power level to a lower one has an effect on the efficiency with which RF power is delivered. It is widely accepted that the farther away from peak RF output a BS is operated, the worse its efficiency is. Hence, in the context of this investigation, it is important to use an accurate BS energy consumption model.

Three versions of the same model are used throughout this article. The BS power consumption model is the one adopted in [20]. It is governed by the following equation:

$$P_{BS,in} = P_{BS,0} + \Delta_P P_{BS,out}, \quad (7)$$

where $P_{BS,in}$ is the required power drawn by the BS in Watts, $P_{BS,0}$ is the idle power consumption *i.e.* when no RF power is used for data transmission, also in Watts, Δ_P is a scaling parameter, and $P_{BS,out}$ is the required output RF power in Watts. The maximum value allowed within this model for $P_{BS,out}$ is $P_{BS,out}^{max}$ which would generally be a design parameter of the BS. The appropriate parameters for a macro BS are $P_{BS,0} = 712$ W, $\Delta_P = 14.5$, and $P_{BS,out}^{max} = 40$ W [20]. A plot of the required input power over the range of operation can be found in Figure 2. This model reflects the current state of BSs.

It is expected that the efficiency of BS hardware will improve in the near future. Also, input power requirements will scale much better with the required output RF power as power amplifier (PA) efficiency is improved and the overall BS consumption reduced [2]. Both these advancements should add to the benefits obtained from BEM and TCoM. The two techniques manipulate the dynamic component of the energy drawn during operation. It is expected that as BSs efficiency is improved, this component will become increasingly dominant over the quiescent drain hence increasing the benefit from BEM and TCoM. This is why two additional

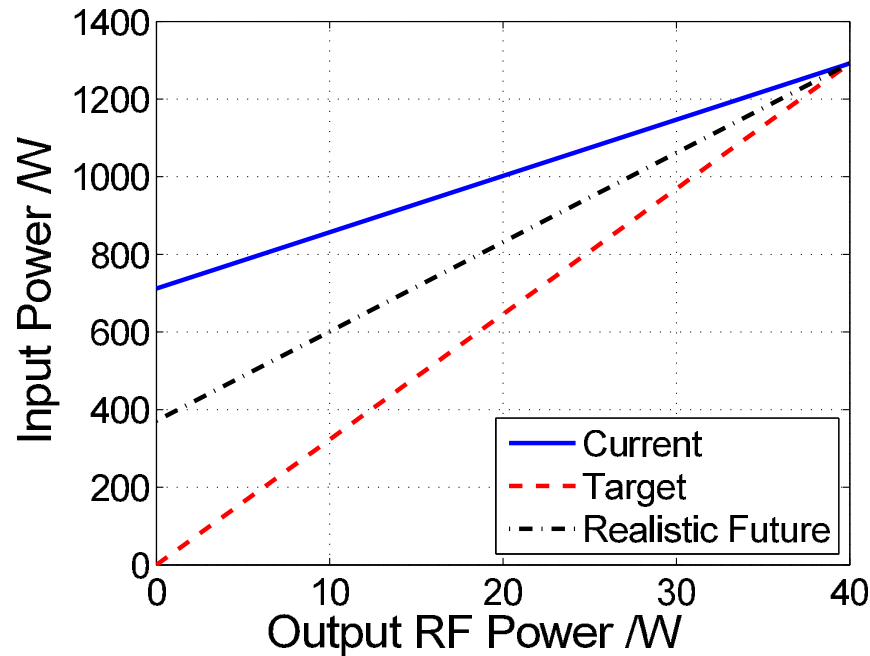


Figure 2 BS model.

consumption models are proposed and adopted. One models the desired ideal performance of the future BS, and the other represents a more realistic proposition. Both can be expressed in the same manner as (7). The parameters for the realistic model are $P_{BS,0} = 371$ W, $\Delta_P = 23.025$, and for the idealistic one - $P_{BS,0} = 0$ W, $\Delta_P = 32.3$.

The first, pessimistic, model is used for evaluating the techniques theoretically. This gives a more realistic view on the gains as the theoretical results make use of idealistic assumptions leading to high predicted gains. However, all three models are used to evaluate the energy savings through simulation in Section 5.

Keeping in mind the operation of BEM, the already calculated ECG can be modified to account for hardware operation at a given RF output as follows:

$$ECG_{BEM}^{TOT} = \frac{P_{BS,in}(P_{BS,out})}{P_{BS,in} \left(\frac{P_{BS,out}}{ECG_{BEM}^{CC}} \right)}. \quad (8)$$

It is important to note that the above equation has a significant drawback. It does not account for the fact

that any initial decrease or increase in interference due to one cell, and hence used energy, is reinforced by an additional one due to the decrease or respectively increase in interference in all of its neighbors. This is a dynamic effect akin to a cocktail party effect which is difficult to model theoretically.

A plot of (8) for a pre-set ratio of $P_{data}/P_{ref} = 3.4$, $\alpha = 2$ and $\phi = 0.25$ can be found in Figure 3. This parameter combination is conservative—low transmission power and high overhead define a scenario where BEM should demonstrate comparatively modest gains. However, even in those conditions the technique provides significant gains. There are two trends to be observed in the figure. First, for a given Γ_q , the gain increases as the total RF output power increases. This means BEM is more useful in bad channel conditions. It also reveals that the variable energy efficiency of the BS which depends on the output RF load has a role to play in determining the overall gain from BEM. Second, for a given output RF power, the gain increases as Γ_q increases. Higher Γ_q s represent less energy efficient modulation schemes against which BEM is able to achieve higher gains.

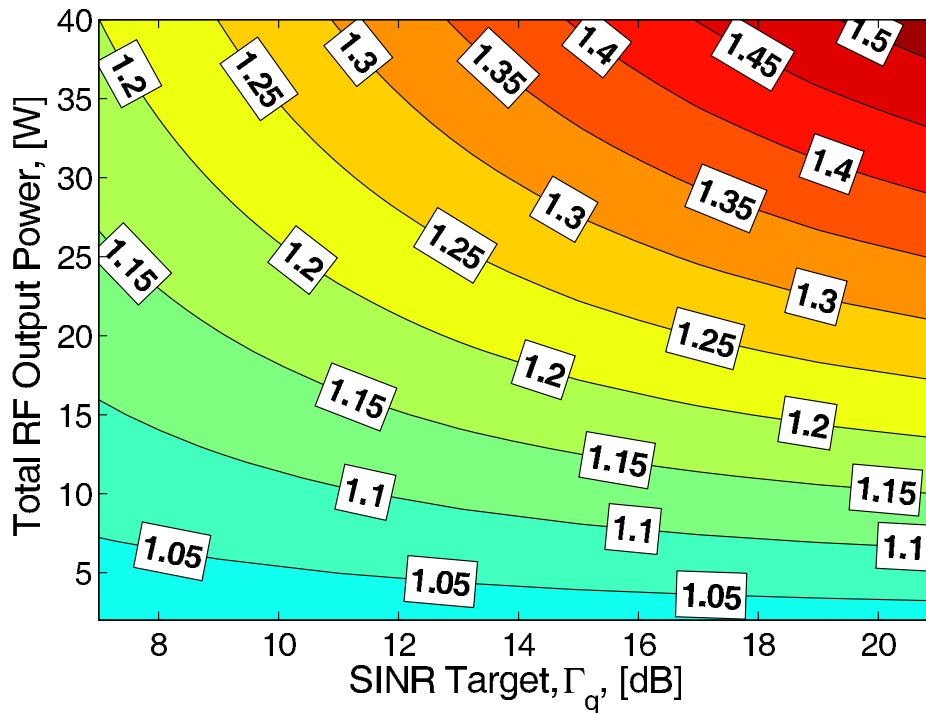


Figure 3 Overall ECG for BEM with fixed data transmission power ($P_{data}/P_{ref} = 3.4$, $P_{data} = 1.53$ W, $\alpha = 2$ and $\phi = 0.25$).

Figure 4 has been realized for a pre-set $\Gamma_q = 11$ dB and $P_{\text{ref}} = 0.4$ W. The parameters are chosen to show that even in high overhead conditions BEM can deliver gains. As the transmission power per RB is increased the gain from BEM increases initially until it converges. This is due to the shift in ratio between overhead and data energy. A low data-overhead ratio means there will not be any gains from BEM. Conversely, a high data-overhead ratio means there are high gains achievable. After the ratio becomes high enough, the achievable gain is no longer affected by overhead as it becomes insignificant.

4. Time compression mode

As shown in the previous section, BEM leads to good results when a user's energy consumption is dominated by energy used for data transmission and not control overhead communication. This means a part of the users cannot benefit from the use of BEM. A straightforward way to reduce the energy consumption of these users is to propose a complementary transmission mode. A similar idea has already been described in [14] for a time based RBs implementation. In the prior work, underutilized RBs are lumped together in time without

any change in the used modulation. RBs that are then not needed are turned off to conserve energy that would otherwise be wasted in control channel transmissions. In this work, RBs that are fully utilized on a relatively low modulation order are lumped together in time, or alternatively in frequency, and a higher order modulation is used. Energy savings are accrued through the reduction in overhead signaling. Naturally, this is done when the channel conditions allow the use of higher order modulation. One of the goals of this article is to determine if the TCoM technique can provide energy saving gains when deployed in realistic scenarios and in what conditions.

A comparison of the three different systems discussed so far can be found in Figure 5.

Decreasing the number of allocated frequency channels in the TCoM system leads to a decrease in the amount of overhead transmissions required, which suggests that users whose energy expenditure is dominated by control channel transmissions will benefit.

4.1. Time vs. frequency implementations

To be able to assess the difference between time and frequency implementations of TCoM, knowledge on

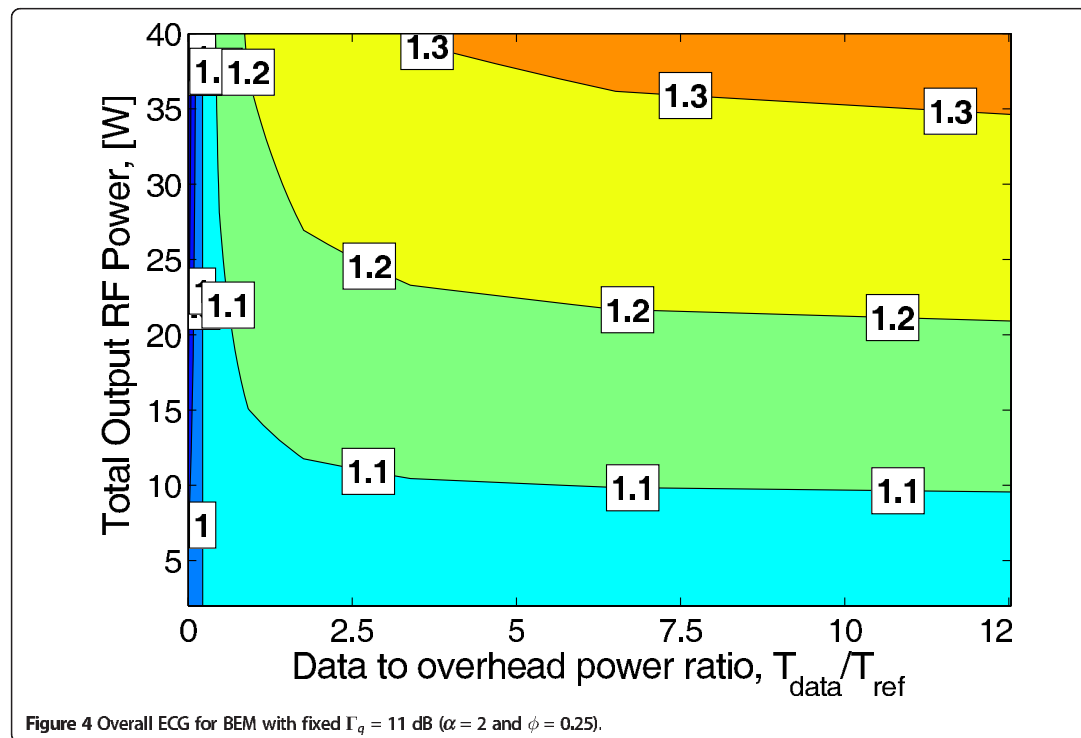
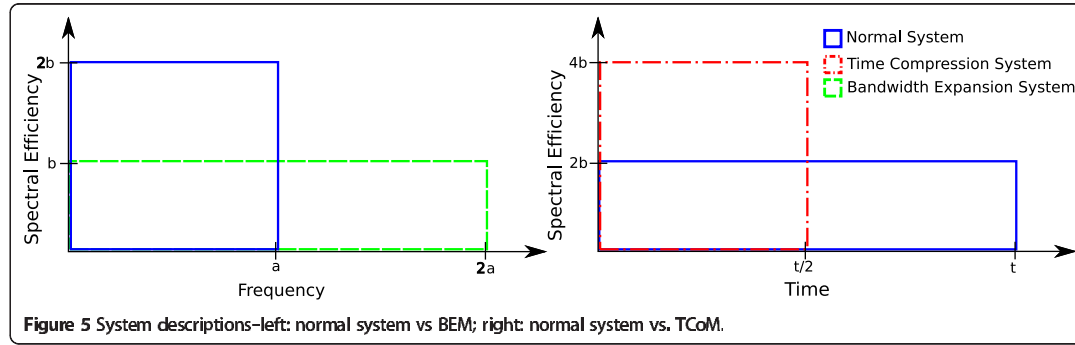


Figure 4 Overall ECG for BEM with fixed $\Gamma_q = 11$ dB ($\alpha = 2$ and $\phi = 0.25$).



how energy costs are generated in the system is required. In general:

$$D = RLB, \quad (9)$$

where D is the delivered payload in bits, R is the spectral efficiency in bits/s/Hz, L is the length of transmission in seconds, and B is the bandwidth in Hz. From this equation it is clear that by increasing the rate, it is possible to either decrease the time it takes for a transmission or decrease its bandwidth footprint. On the other hand, the used energy for a transmission can be calculated as:

$$E_{\text{Used}} = P_{\text{data}}L_{\text{data}}n + P_{\text{ref}}L_{\text{ref}}n, \quad (10)$$

where E_{Used} is the used total energy, P_{data} is the power dedicated to data transmissions, and the overall transmission time $L = L_{\text{data}} + L_{\text{ref}}$ is split between user data and reference signaling. The above can be rewritten with the introduction of ϕ :

$$E_{\text{Used}} = nL((1 - \phi)P_{\text{data}} + \phi P_{\text{ref}}). \quad (11)$$

From the above, it emerges that a linear compression or expansion in either bandwidth or time of a transmission, while retaining the overall delivered payload, leads to the same change in used energy. For example, expanding the bandwidth by a factor of two, will yield the same result as taking twice as long to complete the transmission if we were to retain the size of the delivered payload and the used modulation scheme. In the case of reducing bandwidth or length of transmission, it should be possible to turn off the control channel transmissions on the unused RBs. The number of symbols used for a particular transmission of PDCCH is set by the BS. Explicitly, it is determined by the channel conditions to ensure that the transmission can be reliably decoded [19]. It should be possible to adapt this functionality in LTE, so that it supports the process of eliminating unnecessary overhead to increase energy efficiency.

4.2. ECG derivation

As outlined above, time and frequency implementations of TCoM should not differ in performance, hence only the frequency based system derivation of the gains is presented. To make sure that the two systems deliver the same amount of data, the following needs to be satisfied:

$$R_{\text{TCoM}} = R_{\text{benchmark}}\beta, \quad (12)$$

where the subscripts denote the different systems and β is the time/bandwidth compression factor, which is an integer similar to α . From (12) and Shannon's capacity equation, we can derive the required SINR target for the TCoM system:

$$\tilde{\Gamma}_q = (1 + \Gamma_q)^\beta - 1, \quad (13)$$

where $\tilde{\Gamma}_q$ is the TCoM SINR target. From the basic SINR calculation formula, the required RF power can be calculated:

$$P_q^{\text{RF}} = \frac{N + I_q}{G_{kj}} \tilde{\Gamma}_q. \quad (14)$$

The total expended RF energy to deliver a payload on β RBs in the benchmark system and the same payload in the proposed system can be calculated as:

$$E_{\text{benchmark}} = L \sum_{q=1}^{\beta} ((1 - \phi)P_q + \phi P_{\text{ref}}) \quad (15)$$

$$E_{\text{TCoM}} = L((1 - \phi)\tilde{P}_q + \phi P_{\text{ref}}). \quad (16)$$

The RF ECG can now be calculated from basic principles and (14) as:

$$\text{ECG}_{\text{TCoM}}^{\text{RF}} = \frac{\beta \Gamma_q}{(1 + \Gamma_q)^\beta - 1}, \quad (17)$$

where the assumption is that all used RBs are experiencing nearly identical channel conditions. If the control channel transmissions are to be accounted for as before as well as different channel conditions, the above becomes:

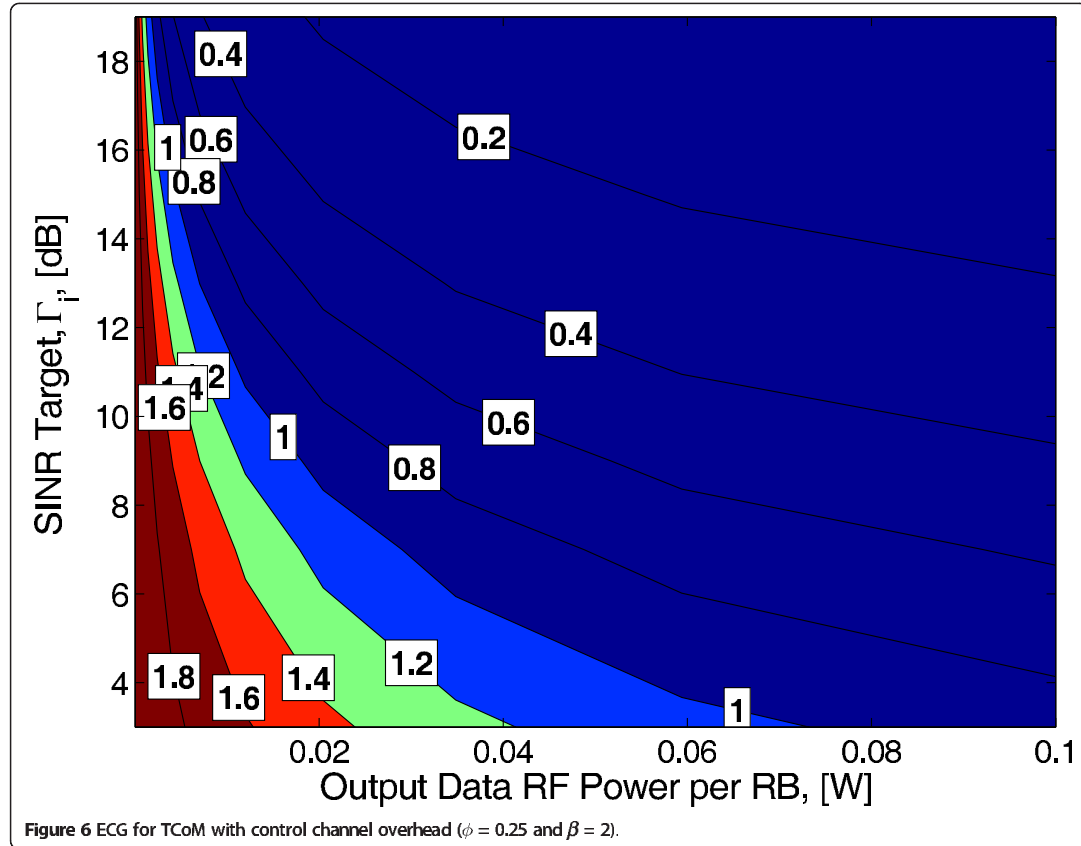
$$ECG_{TCoM}^{CC} = \frac{\beta \sum_{q=1}^n (1 - \phi) \frac{\Gamma_q(N+I_q)}{C_{qj}^d} + \phi P_{ref}}{\sum_{q=1}^n (1 - \phi) \frac{((1+\Gamma_q)^d - 1)(N+I_q)}{C_{qj}^d} + \phi P_{ref}}. \quad (18)$$

The above is plotted in Figure 6 for $\phi = 0.25$ and $\beta = 2$ to underline the gains from TCoM. The figure confirms that the users most likely to benefit from TCoM are ones that enjoy very good channel conditions while not requiring high data throughput, which means their energy consumption is dominated by control channel transmissions. Such users are most likely to be found in the cell center.

Following the manner of the BEM ECG derivation, (18) is modified to account for hardware efficiency:

$$ECG_{TCoM}^{TOT} = \frac{P_{BS,in}(P_{BS,out})}{P_{BS,in} \left(\frac{P_{BS,out}}{ECG_{TCoM}^{CC}} \right)}. \quad (19)$$

Figure 7 presents (19) plotted for a ratio of data to overhead transmission power, P_{data}/P_{ref} , of 0.0012. This value is reasonable considering the path loss difference experienced by a user in the cell center and one on the cell edge. Two trends can be observed. First, the higher the total output RF power, the higher the gain from TCoM. This is due to the fact that the higher the initial loading the more efficient the operation of the system after the required total output power has been reduced through TCoM. Second, the higher the initial SINR target, the lower the gain from TCoM for a given total RF output level. This is due to the fact that more complex modulation techniques are less energy efficient than the simpler ones.



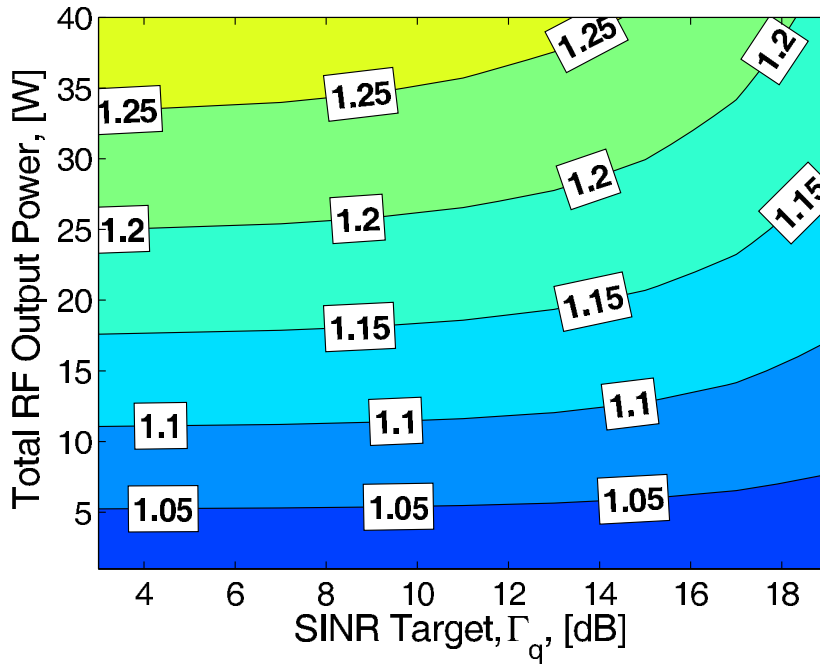


Figure 7 Overall ECG for TCoM with $\phi = 0.25$, $\beta = 2$, and $P_{\text{data}}/P_{\text{ref}} = 0.0012$.

5. Empirical results

To validate the theoretical results, a simulation platform is used to evaluate the performance of EESBS and a system that combines EESBS, BEM, and TCoM, further referred to as the bandwidth scheduling system, against a frequency selective proportional fair (FsPF) scheduler as the one discussed in the Problem Formulation section of [21]. The overall system framework is modeled after LTE—it is an OFDMA based system with parameters taken from the LTE standard proposal documentation.

5.1. Simulation set-up

The simulation parameters employed can be found in Table 1. The number of users per cell is picked from a uniform distribution defined between 5 and 9 users per BS. Each user is assigned a target data rate from a uniform distribution comprised of the following elements—(0.5, 1, 1.5, 2) Mbps. Those result in a bandwidth loading between 20 and 50%. The chosen scenario topology is a two-tiered wrap around a central cell. It is generally accepted that this scenario results in a realistic interference environment in the central cell. Performance data is collected only from this cell. However, all cells operate in the same manner. The channel model used is the

Urban Micro cell model (UMi) as defined in [22]. Frequency selective fading based on the clustered delay line model for scenario B1 is incorporated as described in

Table 1 System parameters

Parameter	Value
Total bandwidth	20 MHz
Carrier frequency	2.14 GHz
Resource bandwidth	180 kHz
Number of RBs	100
Subcarriers per RB	12
BS maximum power	46 dBm
User speed	3 km/h
SINR targets, Γ_q	-6-20 dB
Data rates	0.1523-5.5547 bits/symbol
Users per BS	5-9
Required data rate per user	0.5, 1, 1.5, 2 Mbps
Inter-site distance	870 m
Overhead	12.9%
Control channel SINR target, Γ_{ref}	3.4 dB
Antenna gain	14 dB
Bandwidth expansion factor, α	2
Bandwidth compression factor, β	2

[23]. A infinite size buffer model is used to ensure that all MSs want to transmit at all TSs.

Resource blocks that cannot be used for transmission due to experiencing temporary deep fades or high path loss are not considered during the process of allocation. BEM and TCoM require an RB allocation as a starting point to their operation. The allocation that is achieved by EESBS is used for that purpose. BEM and TCoM then provide iterative improvements over the starting allocation.

The FsPF scheduler operates by applying the proportional fair principle to each RB at a time, and allocating each RB to the user who maximizes the fairness ratio. To avoid initial allocation conflicts, the order in which RBs are considered within each BS is randomized.

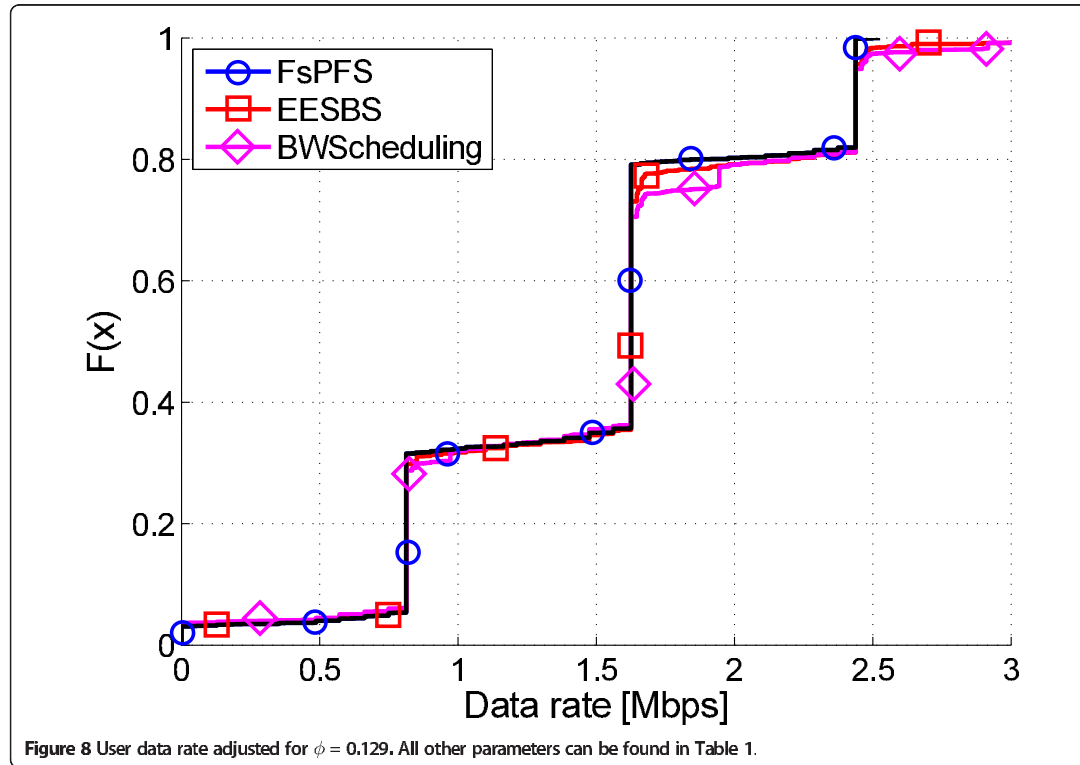
The user specific penalty function used within the EESBS scheduler is $f^k(m_k) = m_k$, where m_k is the number of currently allocated RBs to user k . This means that the more RBs are allocated to a user, the larger the penalty resulting in a fairer allocation. The scheduler also chooses whether to allocate resources based on their effect on the overall cell energy efficiency in BEM and TCoM. If the allocation of a particular RB affects negatively the predicted overall efficiency of the BS, it is not

allocated. The current resource allocation and channel conditions are used to estimate the required energy.

Also, the control channel transmission power, P_{ref} , has to be defined in a meaningful manner. Control channel transmissions need to be able to reliably reach any user within the radius of the BS. Hence, P_{ref} needs to be defined with respect to the cell radius and an SINR target, Γ_{ref} , that defines the modulation used for control channel communication. The following equation is used to calculate the required control channel transmission power per RB:

$$P_{\text{ref}} = \frac{\Gamma_{\text{ref}}(N + 3.7710^{-14})}{G(d)}, \quad (20)$$

where $G(d)$ is the worst path gain for a distance of d between the user and BS including log-normal shadowing up to two sigma away from the mean as that covers 95% of the user population. The value used for the interference component that is to be tolerated is the maximum possible for the given scenario at the cell edge. The data transmission SINR targets are chosen using Shannon's channel capacity equation by adding an additional 3 dB to the calculated SINR targets. This is a



reasonable assumption since two independent studies have determined that LTE achieves link level spectral efficiency that is on average 2 dB away from the Shannon limit [24,25]. This guarantees that the values used are reasonable and close to the current state of the art.

The downlink transmission direction is simulated as it is currently the more energy intensive of the two. Data is collected from one TS after the system has settled to a stable resource allocation. Stability of resource allocation is important since it is desirable that RBs can be used by a user continuously, rather than be constantly contended for by a number of users. Channel condition changes are to be accounted for at the same time. If a more efficient allocation becomes available due to a change in channel conditions, it should be used instead. The theoretical concepts presented in this article can be applied in both the uplink and downlink transmission directions. However, the focus of this study is on downlink transmissions.

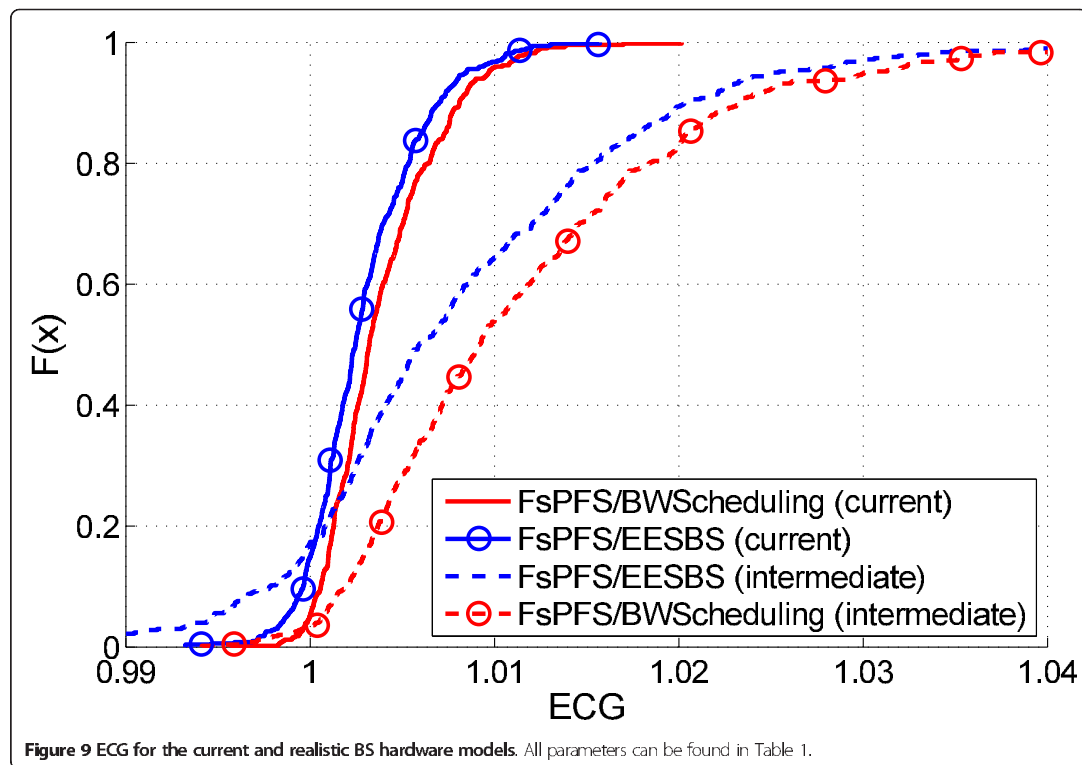
Two parameters are used to evaluate the proposed systems—ECG and data rate.

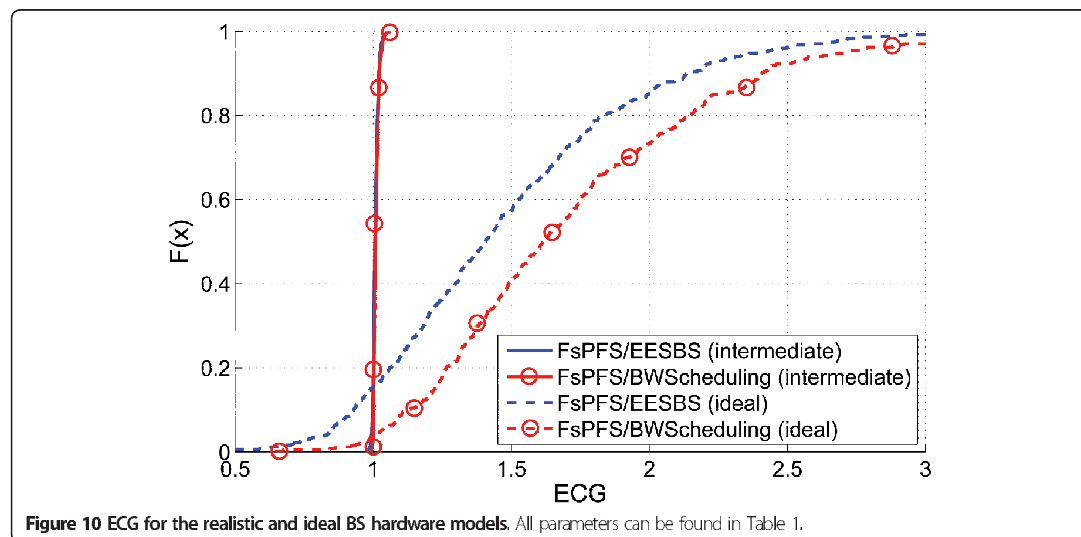
5.2. Results

In the context of this work, it is imperative to compare performance both in terms of data rate and energy efficiency.

Figure 8 presents the data rate performance of the systems. The simulation is set up so that whatever is achieved by the FsPF system is matched by the EESBS and bandwidth scheduling systems. This allows for a meaningful comparison when it comes to energy efficiency between the systems. Notable figures on the graph are 3% of the users experience outage, and the data rate per user is 1.6 Mbps at the 50th percentile. The achieved data rates for the FsPF system do not match the target rates for the scenario since the simulated results are adjusted for overhead as well as being limited by the available modulation transmission modes.

In terms of ECG, the bandwidth scheduling system grants additional gains to EESBS. The results can be found in Figures 9 and 10. For the current and realistic future BS hardware models, the gains presented by the techniques are insignificant. However, for the ideal future BS model, there are significant energy reduction gains. EESBS and the combined system achieve energy reductions with respect to the benchmark of 29 and 38% at the 50th percentile respectively. The very high quiescent state drain with respect to the dynamic component of the BS energy consumption is responsible for the minimal energy gains observed for the current BS hardware model. At this point it is important to note





that the results indicate that the gains increase more than 3-fold when the quiescent drain is halved—from 0.3 to 1%. The combined system as expected achieves higher energy reduction over EESBS as it has more means of decreasing the energy consumption at its disposal. In practice, the real gain would lie between the results for the current and ideal models depending on the evolution of BS hardware in the future.

6. Conclusion

This article presents theoretical results on the performance of BEM in an environment that takes into account control channel overhead and variable energy efficiency in hardware. An expression for the ECG of BEM has been derived while taking into account BS hardware efficiency and control channel overhead. A complimentary technique, TCoM, is also introduced that relies on reduction of overhead to achieve energy gains. The new system, TCoM, is able to help achieve high gains in a realistic simulation scenario. The average reduction due to the combined bandwidth scheduling system for the simulated scenario is up to 38% depending on the BS hardware model. Realistic gains lie between the results presented for the current and ideal BS hardware models and their exact value would depend on the advances made in BS hardware.

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Competing interests

Parts of this work are subject to a patent application [26].

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Energy Efficient Resource Allocation in Wireless Systems with Control Channel Overhead

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Abstract—This paper presents a novel resource scheduling technique named Time Compression Mode (TCoM) that allows energy aware schedulers to decrease the energy consumption within orthogonal frequency division multiple access (OFDMA) type systems – for example the Long Term Evolution (LTE) system. TCoM allows users whose energy consumption is dominated by control channel overhead, to reduce their overall energy expenditure by reducing the number of resource blocks (RBs) allocated to them. This leads to an overall reduction in the used energy due to the decrease in energy used for overhead transmission. To ensure correct operation, TCoM has to be coupled with an energy aware scheduler. This combination not only reduces the used energy, but is also able to increase the achieved user data rate. Simulation results show that the data rate performance is equivalent for 86.8% of the users, however the remaining 13.2% enjoy approximately double the data rate delivered by the benchmark. The overall used energy is decreased by 26% on average. These results are achieved for an future base station (BS) overall hardware efficiency model.

I. INTRODUCTION

Resource allocation is certainly one of the facets within wireless communications that can be controlled to help achieve energy efficiency. Song *et al.* [1] have recently evaluated the energy consumption of the MaxWeight scheduling algorithm in multi-hop wireless networks. They have then improved on it with a new energy scheduling algorithm to achieve gains of up to 25%. Schurgers *et al.* [2] take a different approach where they try to optimize the non-preemptive scheduling in a system by scaling the modulation and hence trading energy efficiency for delay. They achieve gains of up to 50%. Zhang *et al.* [3] propose a low complexity algorithm that is based on the principle of simultaneous resource and power allocation.

The target of this paper is to present a novel resource allocation technique, TCoM, which is able to optimize an already established RB allocation in light of both hardware efficiency and control channel overhead in a wireless cellular network. It operates on the principle that high energy consumption due to the use of complex modulation can be offset by the reduction in control channel overhead when fewer RBs are used to achieve an energy efficient allocation. This work targets the downlink transmission direction.

The rest of the paper is organized as follows. Section II describes the studied system and the assumptions made throughout this work. Section III provides a description of TCoM, as well as a theoretical gain derivation. Section IV introduces an energy-efficient scheduling algorithm that enables

the correct use of TCoM. Section V presents the simulation platform used for empirical testing. The paper concludes with Section VI.

II. SYSTEM MODEL

The system considered is modeled after an OFDMA LTE type system. This section focuses on the models used for hardware efficiency at the BS, control channel overhead, and power control.

Typically, cellular systems have a broadcast channel which carries information that allows the remaining data channels in the system to be configured and used for communication. The LTE makes use of a Physical Broadcast Channel (PBCH) which carries a 'Master Information Block' (MIB), as well as a Physical Downlink Control Channel (PDCCH). Both are a part of the Physical Downlink Shared Channel (PDSCH) – they are allocated particular resources in time and frequency [4].

We assume that the PBCH, PDCCH, reference, and synchronization signals are transmitted with a constant power, so that they can achieve coverage of the complete intended cell site. PBCH information is transmitted every 40 ms or every 40 sub-frames [4]. In addition to that, every sub-frame contains PDCCH data as well as reference signals. The PDCCH data can be configured to occupy the first 1, 2, or 3 OFDM symbols in each time slot of each RB.

If we are to quantify the total overhead due to PBCH and PDCCH using the values presented above, we find that it varies between approximately 12.9% and 26.9% [4]. The contribution of PBCH is relatively minor – approximately 1.3% relative to the complete system. It is also important to note that PDCCH could be turned off if the particular frequency resource blocks are not going to be used, whereas PBCH cannot be turned off as it is required so that new users can connect to the network. Hence, only the overhead from PDCCH will be considered in this paper.

Keeping in mind the above, control channel overhead due to PDCCH can be modeled as a transmission that takes a fraction of the time slot (TS) at a constant pre-set radio frequency (RF) power. This can be expressed as:

$$E_{\text{Used}} = n L ((1 - \phi)T_{\text{data}} + \phi T_{\text{ref}}), \quad (1)$$

where E_{Used} is the used energy, n is the total number of RBs allocated, L is the duration of transmission, ϕ is the amount of

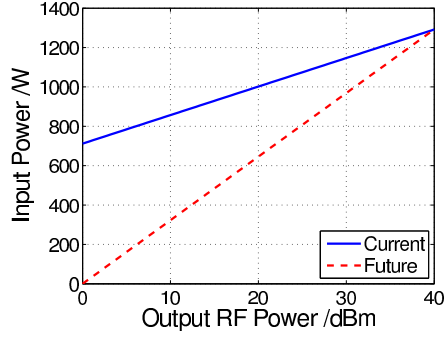


Fig. 1. BS hardware efficiency models

control channel overhead expressed as a fraction, T_{data} is the data transmission power, and T_{ref} the control channel overhead transmission power.

Switching the operation of a BS from one output RF power level to a lower one has an effect on the efficiency with which RF power is delivered. It is widely accepted that the farther away from peak RF output a BS is operated, the worse its efficiency is [5]. Hence, in the context of this investigation, it is important to use an accurate BS energy consumption model.

Two models are used throughout this paper. The first BS power consumption model is the one adopted in [5]. It is governed by the following equation:

$$P_{\text{in}} = P_0 + \Delta_p P_{\text{out}}, \quad (2)$$

where P_{in} is the required power drawn by the BS in Watt, P_0 is the idle power consumption *i.e.* when no RF power is used for data transmission, also in Watt, Δ_p is a scaling parameter, and P_{out} is the required output RF power in Watt. Its maximum value is $P_{\text{out}}^{\text{max}}$ which would generally be a design parameter of the BS. The appropriate parameters for a macro BS are $P_0 = 712$ W, $\Delta_p = 14.5$, and $P_{\text{out}}^{\text{max}} = 40$ W [5]. A plot of the required input power over the range of operation can be found in Fig. 1 as the continuous line. This model reflects the current state of BSs.

It is expected that the efficiency of BS hardware will improve in the near future. Input power requirements will scale much better with the required output RF power as power amplifier (PA) efficiency is improved and the overall BS consumption reduced [6]. It is expected that the dynamic component will become increasingly dominant over the quiescent drain. This is why a second consumption model is proposed and adopted. It models the desired future behavior of the BS consumption. It can be expressed as:

$$P_{\text{in}} = \frac{P_{\text{in}}^{\text{max}} P_{\text{out}}}{P_{\text{out}}^{\text{max}}}, \quad (3)$$

where $P_{\text{in}}^{\text{max}} = 1292$ W is the maximum input power for the BS. This value is chosen to adhere to the maximum energy consumption in (2). A plot of the behavior of the model over the range of operation of the BS can be found in Fig. 1 as the dashed line.

The first, pessimistic, model is used for evaluating TCoM theoretically. This gives a more realistic view on the gains

as the theoretical results make use of idealistic assumptions leading to high predicted gains. However, both models are used to evaluate the energy savings through simulation in section V.

Lastly, to correctly evaluate the energy performance of TCoM against a benchmark, both systems need to operate at their most efficient point given the test scenario. In order to achieve this, power control needs to be employed. The algorithm of choice here is the Foschini-Miljanic power control algorithm [7] due to its simplicity and low computational overhead. It is based on the following iterative control equation:

$$T_i^k(t) = \frac{\Gamma_i}{\gamma_i^k(t-1)} T_i^k(t-1), \quad (4)$$

where $T_i^k(t)$ is the transmission power used for user k on RB i for TS t , Γ_i is the signal to interference plus noise ratio (SINR) target for RB i , and $\gamma_i^k(t-1)$ is the achieved SINR at the prior time instance. The power control subroutine should be allowed to run until the transmission power vector has converged in the full system level simulations.

III. TIME COMPRESSION MODE

In TCoM, RBs that are fully utilized by a single user on a relatively low modulation order are lumped together in time, and/or alternatively in frequency, and a higher order modulation is used. Energy savings are accrued through the reduction in overhead signaling due to turning off the now unused RBs. Naturally, this is done when the channel conditions allow the use of higher order modulation. Hence, bit error rate changes between modulations are not considered. The goal of this paper is to determine if TCoM can provide energy saving gains when deployed in realistic scenarios and in what conditions. These gains should come with no detriment to user and system throughput as well as fairness in the system.

Generally, time and frequency implementations of TCoM should not differ in performance, due to the fact that changes in the length or bandwidth of a transmission have the same effect on the required transmission energy. Hence, only the bandwidth based system derivation of the gains is presented. To make sure that TCoM delivers the same amount of data as is without it being enabled, the following needs to be satisfied:

$$R_{\text{TCoM}} = R_{\text{benchmark}} \beta, \quad (5)$$

where R is the user data rate, and the subscripts denote the different systems and β is the time/bandwidth compression factor, which denotes the number of RBs to be pooled together. The compression factor has to be such that the resulting number of used RBs after employing TCoM is integer. From (5) and Shannon's capacity equation, we can derive the required SINR target for the TCoM system:

$$\tilde{\Gamma}_i = (1 + \Gamma_i)^\beta - 1, \quad (6)$$

where $\tilde{\Gamma}_i$ is the TCoM SINR target. From the SINR requirements, the required RF power can be calculated:

$$T_i^{\text{RF}} = \frac{N + I_i}{G_{kj}} \tilde{\Gamma}_i, \quad (7)$$

where N is the noise floor, I_i is the interference on RB i , and G_{kj} is the path gain on the link between user k and his assigned BS j . The total expended RF energy to deliver a payload on β RBs in the benchmark system and the same payload in the proposed system can be calculated as:

$$E_{\text{benchmark}} = L \sum_{i=1}^{\beta} ((1-\phi)T_i + \phi T_{\text{ref}}) \quad (8)$$

$$E_{\text{TCoM}} = L \left((1-\phi)\tilde{T}_i + \phi\tilde{T}_{\text{ref}} \right). \quad (9)$$

The RF energy consumption gain (ECG) [6] for TCoM versus a standard system without taking control channel overhead in account can be calculated as:

$$\text{ECG}_{\text{TCoM}}^{\text{RF}} = \frac{E_{\text{benchmark}}}{E_{\text{TCoM}}} = \frac{\beta \Gamma_i}{(1 + \Gamma_i)^\beta - 1}, \quad (10)$$

where the assumption that all used RBs are experiencing nearly identical channel and interference conditions. If the control channels are to be accounted for as well as different channel conditions, the above becomes:

$$\text{ECG}_{\text{TCoM}}^{\text{CC}} = \frac{\beta \sum_{i=1}^n (1-\phi) \frac{\Gamma_i(N+I_i)}{G_{kj}} + \phi T_{\text{ref}}}{\sum_{i=1}^n (1-\phi) \frac{((1+\Gamma_i)^\beta - 1)(N+I_i)}{G_{kj}} + \phi T_{\text{ref}}}. \quad (11)$$

The case for TCoM can be made when the control channel overhead in the system is high and a user's energy consumption is dominated by the power used for control information. This means that the users most likely to benefit from TCoM are ones that enjoy very good channel conditions while not requiring high data throughput. To account for BS hardware efficiency, (2) and (11) can be combined to achieve:

$$\text{ECG}_{\text{TCoM}}^{\text{TOT}} = \frac{P_{\text{in}}(P_{\text{out}})}{P_{\text{in}} \left(\frac{P_{\text{out}}}{\text{ECG}_{\text{TCoM}}^{\text{CC}}} \right)}, \quad (12)$$

where $P_{\text{in}}(P_{\text{out}})$ is the general form (1) and (2) would take if re-written as functions.

If we were to plot (12) for a cell center user, we would observe two trends. First, the higher the total output RF power, the higher the gain from TCoM. This is due to the fact that the higher the initial loading the more efficient the operation of the system after the required total output power has been reduced through TCoM. Second, the higher the initial SINR target, the lower the gain from TCoM for a given total RF output level. This is due to the fact that the more complex modulation techniques are inherently less energy efficient than their less complex counterparts. Cell edge users are not expected to experience a reduction in energy since the required additional energy for communication would far outweigh the reduced communication overhead.

A limitation of the hereby presented model is that interference is considered constant. Also, the value of the compression parameter, β , is very important. In general, high values are unusable as the channel conditions and the maximum transmit power combination are unable to support transmissions. In practice, values higher than 4 are unlikely to be used.

IV. SCHEDULING REQUIREMENTS

A major component of any energy efficient wireless communication system is the resource scheduler. A well designed system needs to be aware of the energy costs that different resource allocation decisions entail. This allows any subsequent energy performance enhancements in the scheduling to be incorporated as alternative allocation options that can be evaluated and possibly enacted by the scheduler. Moreover, TCoM would not be able to function efficiently in a continuously changing environment without an energy aware scheduler.

This can be achieved through modifying the score based scheduler [8]. The score based scheduler in its basic form outlined by Bonald [8] cannot be used to enhance energy efficiency while not compromising fairness and delivered data rate. The metric used for rating the resources needs to be changed, as well as the whole routine adapted to OFDMA rather than TDMA systems. A modified scheduler is proposed in the rest of this section, and will be henceforth referred to as energy efficient score based scheduler (EESBS).

To promote energy efficiency, RBs that can be used in highly energy efficient manner need to be allocated first. The use of a metric for rating them within the score based scheduler that measures the energy efficiency of the RB can achieve the desired result. A large number of metrics can be used – total energy used, energy per bit delivered etc. In this work, total energy going into the BS is chosen so that the overall system efficiency can be optimized. A RB's energy performance is compared to that of the remaining RBs available for allocation to that user, and scores are assigned. Moreover, when a conflict between users arises – the user who can use the RB most efficiently among the contending users is allowed to transmit on it. The rest of the users are allocated their next best RB.

Also, fairness among users has to be assured while satisfying each user's data rate requirement as best as possible. To ensure that, users are allocated one RB at a time until their service requirements are met. By doing so, users with low required data rate do not suffer due to the presence of high demand users who require a large number of RBs.

The equation for calculating the scores is:

$$s_i^k(t) = 1 + \sum_{j=1, j \neq i}^M \mathbb{I}_{E_i^k(t) > E_j^k(t)} + f^k(m_k), \quad (13)$$

where $s_i^k(t)$ is the score of user k at slot t on RB i , \mathbb{I} is the indicator function which returns 1 if the condition in the brackets is true and 0 otherwise, $E_i^k(t)$ is the energy metric, M is the total number of RBs and $f^k(m_k)$ is a penalty function based on the number of already allocated RBs for the user. Lower scores indicate higher desirability for allocation. It is in theory possible to assign each user a separate penalty function, as well as to have a penalty function that prioritizes users based on different criteria, such as vulnerability, subscription plan *etc.*. This makes EESBS a versatile and easy to tailor scheduling technique.

A pseudo code implementation of the score based scheduler can be found in Algorithm 1. If further prioritization of users is required, the population can be split in different groups which

TABLE I
SYSTEM PARAMETERS

Parameter	Value
Total Bandwidth	20 MHz
Carrier Frequency	2.14 GHz
Resource Bandwidth	180 kHz
Number of Resource Blocks (RBs)	100
Subcarriers per RB	12
BS Maximum Power	46 dBm
User Speed	3 km/h
SINR targets, Γ_i , for benchmark, TCoM	8.3, 15.7 dB
Data rates	2, 4 bits/symbol
Users per BS	25
Resources per User, x	2, 1
Inter-site distance	1000 m
Time compression factor, β	2
Overhead	12.9%
Control channel SINR target, Γ_{ref}	3.4 dB
Antenna gain	14 dB

are allowed to allocate a number of priority RBs in order of importance. The algorithm implementation is not centralized and the order in which BSs are considered is not important. The only requirement is that no two neighbouring BSs execute EESBS and TCoM at the same time.

Algorithm 1 Amended score-based scheduler

```

INITIALIZE the number of required RBs for each user
while Users require RBs do
  CALCULATE scores for all users based on (13)
  for  $i = 1$  to number of BSs do
    FIND best RB based on calculated scores for each user connected
    to this BS
    if User's best RB is not allocated AND is usable AND is not another
    user's best RB then
      ALLOCATE RB to user
    end if
    if There were conflicting RBs between users then
      RESOLVE conflicts by allocating RB to most efficient or priority
      user, and allocate next best RBs to the remaining users
    end if
  end for
  if There are no available RBs for allocation OR no users require more
  RBs then
    EXIT while loop
  end if
end while
RUN power control algorithm

```

V. EMPIRICAL RESULTS

A. Simulation Set-up

The parameters used in the simulation framework can be found in Table I. Those result in a bandwidth loading of approximately 60%, *i.e.* 60% of the RBs are occupied. The chosen scenario topology is a two-tiered wrap around a central cell. It is generally accepted that this scenario results in a realistic interference environment in the central cell. Performance data is collected only from this cell. However, all cells operate in the same manner.

The channel model used is the Urban Micro cell model (UMi) as defined in [9]. Selective frequency fading based on the clustered delay line model is incorporated as well [10]. A constant size buffer model is used to ensure that all users want to transmit the same amount of data at all time slots. Hence, the required data rate for all users is the same.

TCoM is compared to a Round Robin (RR) benchmark scheduler. Each user is assumed to require a set number of

frequency resource blocks while simulating the benchmark system. RBs that cannot be used for transmission due to poor channel conditions are not considered during the process of allocation. This effectively results in proportional fair (PF) scheduling since all RBs are used with the same modulation scheme and only one at a time is allocated alternating between users until all users are satisfied or there are no more RBs to allocate.

The TCoM system requires an RB allocation as a starting point to its operation. The achieved stable EESBS allocation is used for that purpose.

The user specific penalty function used within the EESBS scheduler is $f^k(m_k) = m_k$, where m_k is the number of currently allocated RBs to user k . This means that the more RBs are allocated to a user, the larger the penalty resulting in a fairer allocation. The scheduler also chooses whether to allocate resources based on their effect on the overall cell energy efficiency in TCoM. If the allocation of a particular RB affects negatively the predicted overall efficiency of the BS, it is not allocated. The current resource allocation and channel conditions prior to updating the allocation are used to estimate the required energy.

Also, the control channel transmission power, T_{ref} , has to be defined in a meaningful manner. Control channel transmissions need to be able to reliably reach any user within the radius of the BS. Hence, T_{ref} needs to be defined with respect to the cell radius and an SINR target, Γ_{ref} , that defines the modulation used for control channel communication. The following equation is used to calculate the required control channel transmission power per RB:

$$T_{\text{ref}} = \frac{\Gamma_{\text{ref}}(N + 3.77 \times 10^{-14})}{G(r)}, \quad (14)$$

where $G(r)$ is the maximum path gain between a user at the cell edge and BS including two standard deviations of log-normal shadowing, and thus should account for 95% of cell edge users. The value, 3.77×10^{-14} , used for the maximum interference component that is to be tolerated again covers 95% of users at the cell edge. This means that less than 1% on average of the total number of users in the cell will experience outage.

The data transmission SINR targets for the modulations used are chosen using Shannon's channel capacity equation by adding an additional 3 dB to the calculated SINR targets. This guarantees that the values used are within less than 5 – 10% deviation from the state of the art [11, 12].

The downlink transmission direction is simulated as it is currently the more energy intensive of the two. Data is collected from one time slot after the system has settled to a stable resource allocation. Stability of resource allocation is important since it is desirable that RBs can be used by a user continuously, rather than be constantly contended for by a number of users. Channel conditions changes are to be accounted for at the same time. If a more efficient allocation becomes available due to a change in channel conditions, it should be effected into place. It is important to note that TCoM can be easily adapted to also work in the uplink direction.

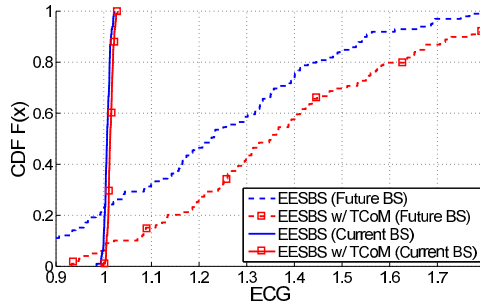


Fig. 2. Simulated ECG with respect to RR using $\phi = 0.129$ and $\beta = 2$

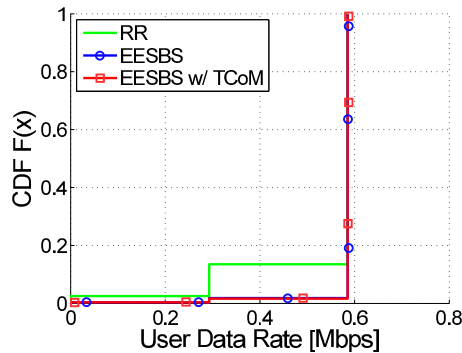


Fig. 3. User data rate with $\phi = 0.129$ and $\beta = 2$

Two parameters are used to evaluate the performance of TCoM against the benchmark system – ECG and data rate.

B. Results

In the context of this paper, it is imperative to compare performance both in terms of data rate and energy efficiency.

Fig. 2 presents the energy performance of the systems. In terms of ECG, TCoM grants additional gains to EESBS. TCoM improves the performance over EESBS by a significant 46.1% for the future BS model which is evident in the large gap between the two dashed curves in the graph. For the current BS model, the gain over the RR scheduler is largely insignificant. This is due to the large quiescent energy draw which diminishes any gains in the dynamic portion of the energy consumption. The results for a future BS hardware model show a greater improvement. EESBS reduces the energy consumption as compared to RR by 19% at the 50th percentile – TCoM does so by approximately 26%. In practice, the real gain would lie between the results for the two models depending on the evolution of BS hardware in the future.

Not only is the energy efficiency improved, but the throughput for 13.2% of the users is almost doubled from 0.3 to 0.6 Mbps for EESBS and TCoM as depicted in Fig. 3. The outage probability is decreased from 2.2% to 0.3%. 98.3% of the users achieve the target rate of 0.58 Mbps as opposed to only 86% for RR. The stepwise behavior of the graph is due to users being allocated an integer number of RBs at a pre-set modulation. Although the target rates of all users are fixed, the RR system is not able to satisfy all users' requirements, hence leaving room for the aforementioned improvement due

to EESBS coupled with TCoM. The improvement in data rate is the reason for the 22% of cases in which EESBS underperforms RR in terms of overall energy efficiency.

VI. CONCLUSION

This paper has presented a novel transmission mode, TCoM, that coupled with an energy aware scheduler, EESBS, is able to provide not only energy savings, but also improve the user data rate. The achieved energy reduction depends not only on the particularities of TCoM but also on the hardware energy efficiency at the BS. This is evident in both the theoretical and empirical results. The improvement in energy efficiency is highest for the targeted future BS model. TCoM provides a reduction in required energy by approximately 26%. However, regardless of the BS hardware efficiency model, TCoM is able to approximately double the achieved data rate for 13.2% of the users deployed.

VII. ACKNOWLEDGMENT

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(54) **OPERATION OF A TELECOMMUNICATIONS SYSTEM**

Publication Classification

(75) Inventors: **Stefan Ivanov Videv**, Edinburgh (GB); **Harald Haas**, Edinburgh (GB); **Rui Wang**, Livingston (GB); **John Thompson**, Edinburgh (GB)

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(57) **ABSTRACT**

(73) Assignee: **The University Court of the University of Edinburgh**, Edinburgh (GB)

A method of operating a mobile telecommunications system having a base station, a plurality of users and a plurality of spectral resource blocks, some of which are not allocated to users. The method includes, (a) for each user, assigning a score to each resource block based on the energy efficiency with which the user can use the resource block, and determining which of the plurality of resource blocks is favored, i.e. has a score indicating that it will be the most energy efficient for the user. For each user, either (b) if the user's favored resource block is not allocated, and is not favored by any other user, that resource block is allocated to that user; or (c) in the event that the same resource block is favored by more than one user, it is allocated to the user who will use it with the greatest energy efficiency.

(21) Appl. No.: **13/197,422**

(22) Filed: **Aug. 3, 2011**

(30) **Foreign Application Priority Data**

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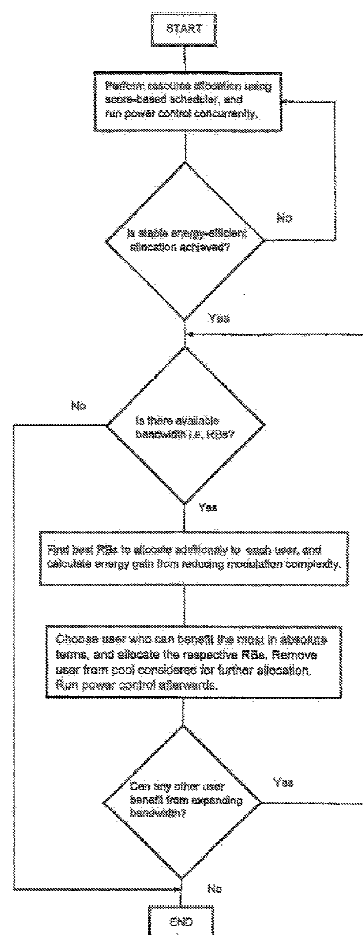
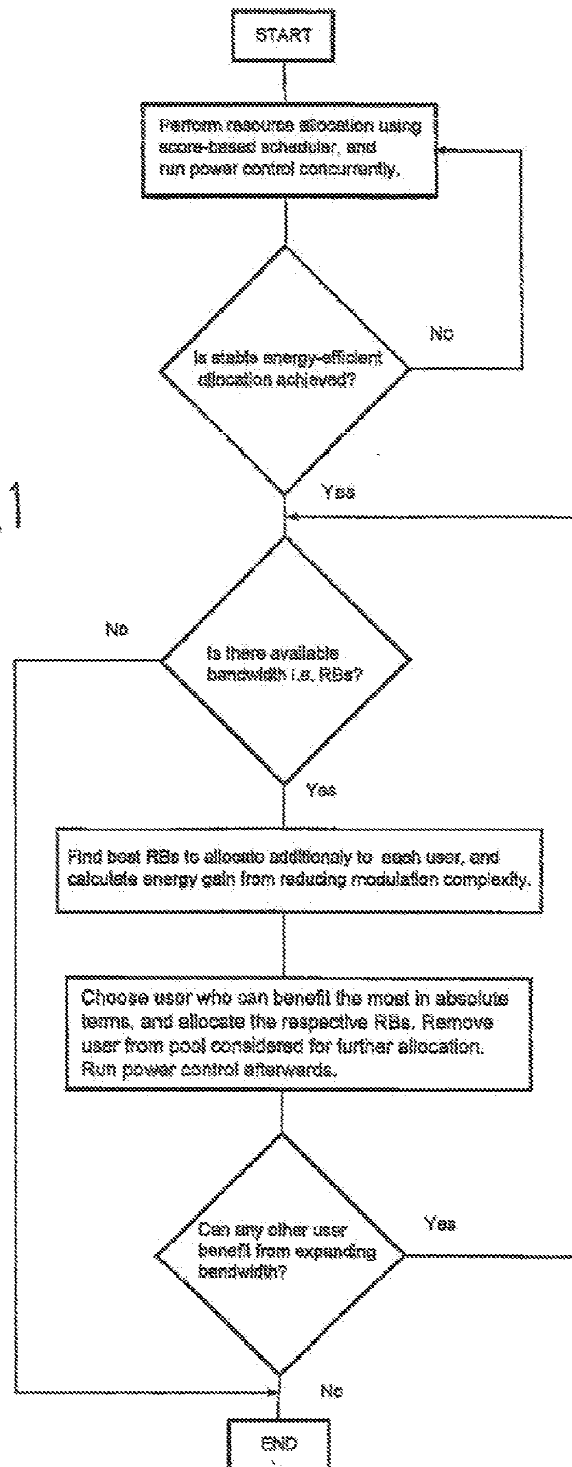


Fig. 1



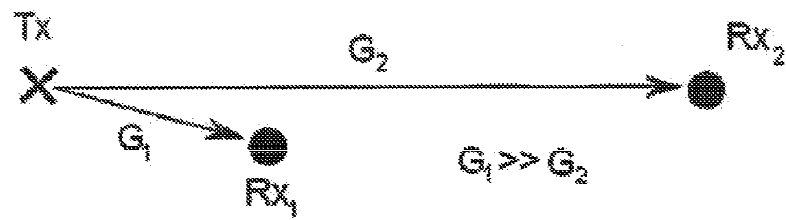


Fig. 2a

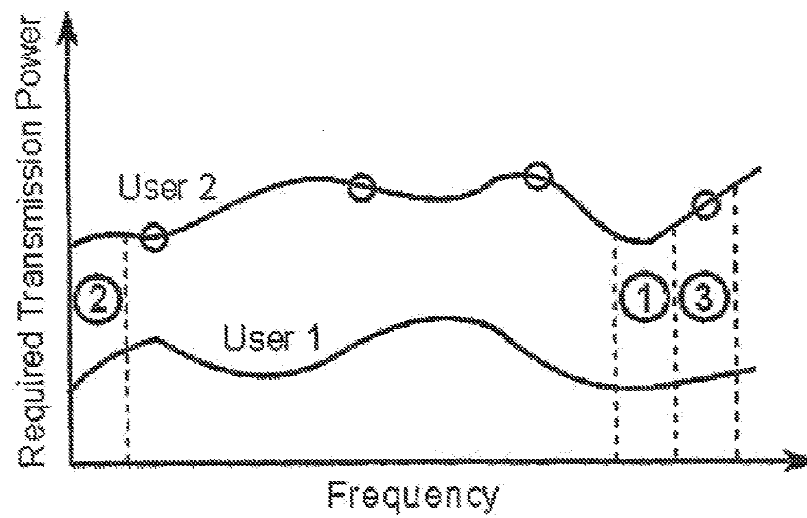


Fig. 2b

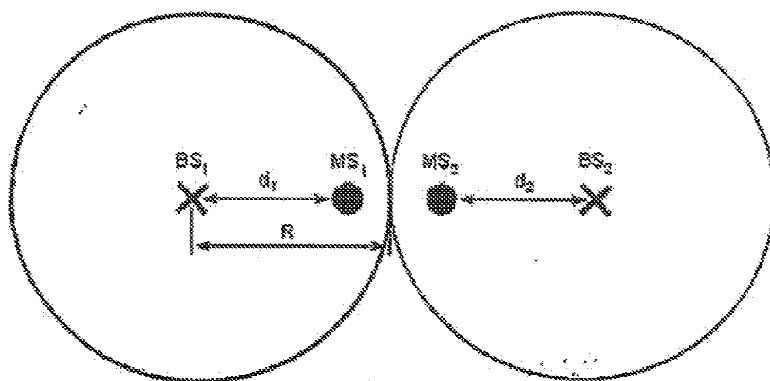


Fig. 3

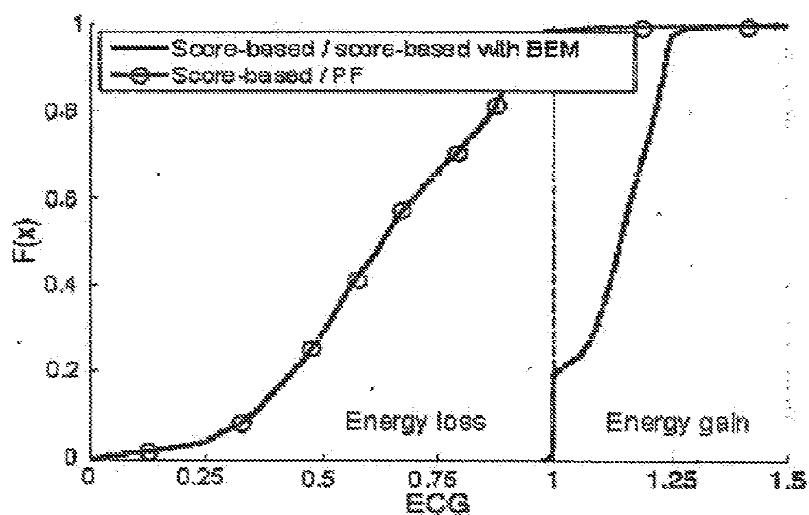


Fig. 5

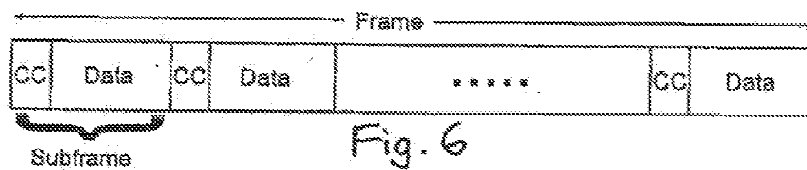


Fig. 6

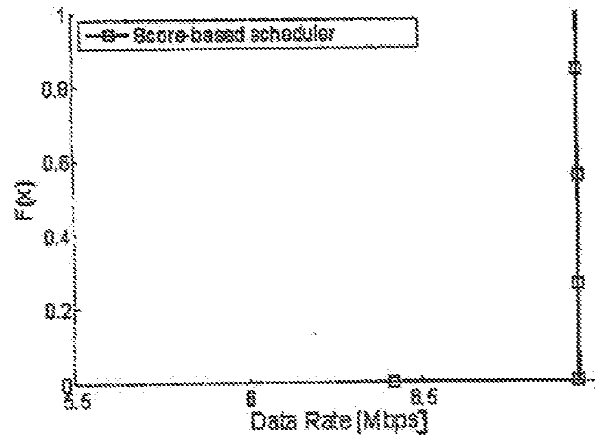


Fig. 4a

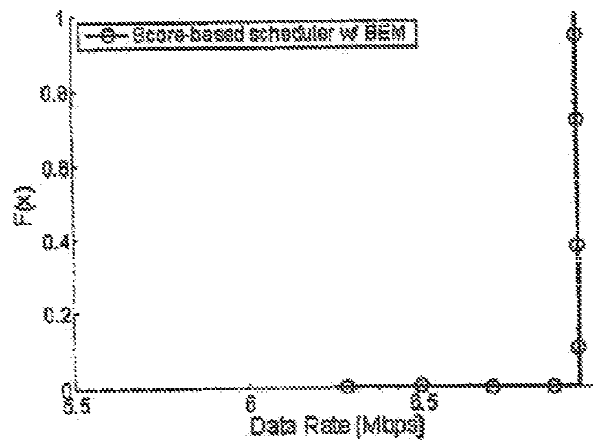


Fig. 4b

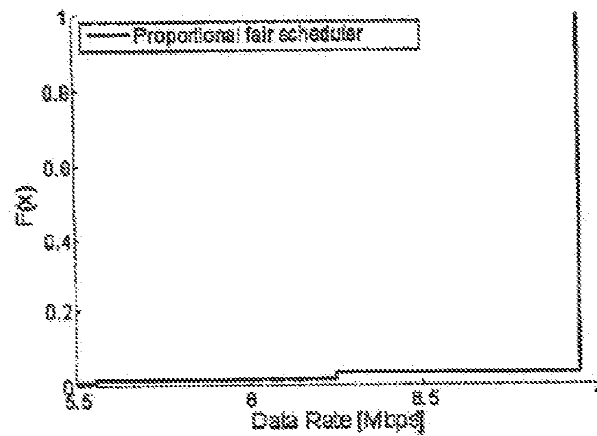


Fig. 4c

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OPERATION OF A TELECOMMUNICATIONS SYSTEM

BACKGROUND TO THE INVENTION

[0001] This invention relates to a method of operating a mobile telecommunications system and to a base station for implementing the method.

[0002] Much current research work is focused on joint efficient resource allocation and power control that minimize interference and maximize system capacity. Overall network capacity is adopted as the measure of system performance.

[0003] In contrast, the present invention is concerned with introducing a technique that preserves system performance while minimizing the expended energy.

[0004] F. Meshkati, V. Poor, and S. Schwartz, "Energy-Efficient Resource Allocation in Wireless Networks: An Overview of Game Theoretic Approaches," *IEEE Signal Processing Magazine: Special Issue on Resource-Constrained Signal Processing, Communications and Networking*, May 2007, focuses on trade-offs between throughput, delay, network capacity and energy efficiency. However, the approaches analyzed assume no cooperation between users. Özgür Oyman and A. J. Paulraj, "Power-Bandwidth Tradeoff in Dense Multi-Antenna Relay Networks," *IEEE Transactions on Wireless Communications*, vol. 6, pp. 2282-2293, June 2007, explores the power-bandwidth trade-off in dense multi-antenna relay networks. However, this work is based on multi-antenna relay beamforming, and is primarily focused on enhancing spectral efficiency rather than minimizing expended energy. S. Sinanovic, N. Serafimovski, H. Haas, and G. Auer, "Maximising the System Spectral Efficiency in a Decentralised 2-link Wireless Network," *Eurasip Journal on Wireless Communications and Networking*, vol. 2008, p. 13, 2008, focuses on the effect of power allocation on spectral efficiency in 2-link decentralized networks. Their results are particularly interesting with regard to the effects interference has on spectral and hence energy efficiency. P. Omiyi, H. Haas, and G. Auer, "Analysis of TDD Cellular Interference Mitigation Using Busy-Bursts," *IEEE Transactions on Wireless Communications*, vol. 6, no. 7, pp. 2721-2731, July 2007, proposes a novel interference avoidance technique based on in-band signaling that also has implications towards energy conservation. A good overview of energy efficient network protocols for wireless networks can be found in C. T. Jones, K. M. Sivalingam, P. Agrawal, and J. C. Chen, "A Survey of Energy Efficient Network Protocols for Wireless Networks," *Wireless Networks*, vol. 7, pp. 343-358, 2001. The authors consider a variety of topics, including low-power design within the physical layer, sources of power consumption within the mobile terminals, energy efficient MAC protocols, as well as protocols on the transport and application layers.

[0005] The concept of an energy efficient "sleep mode" has been investigated in W. Ye, J. Heidemann, and D. Estrin, "An Energy-Efficient MAC Protocol for Wireless Sensor Networks," *INFOCOM 2002: Twenty-First Annual Joint Conference of the IEEE Computer and Communications Societies, Proceedings*, IEEE, vol. 3, pp. 1567-1576, 2002 and K. Han and S. Choi, "Performance Analysis of Sleep Mode Operation in IEEE 802.16e Mobile Broadband Wireless Access Systems," *Vehicle Technology Conference*, 2006: VTC 2006-Spring, IEEE 63rd, vol. 3, pp. 1141-1145, September 2006. These publications focus on an on/off approach to sleep cycles in decentralized networks. Mobile stations (MSs) are allowed to turn off for periods of time depending on the traffic

conditions. There are algorithms which iteratively increase sleep time if there are no requests to the MS. R. Wang, J. Thompson, and H. Haas, "A Novel Time-Domain Sleep Mode Design for Energy-Efficient LTE," *International Symposium on Communications, Control and Signal Processing*, March 2010, focuses on a more active approach, where energy is saved by cutting down on control signaling during low traffic periods.

SUMMARY OF THE INVENTION

[0006] It is an aim of the invention to allocate resources in wireless networks in an energy efficient manner, thus potentially saving operational costs and CO₂ emissions.

[0007] The invention considers the users of a wireless system and allocates bandwidth resources in an energy-efficient manner for each user. It is particularly applicable to LTE (long term evolution) OFDMA (orthogonal frequency division multiple access) systems in which frequency resources are available in quantum resource blocks (RBs).

[0008] The invention uses an energy efficiency measure in the process of scheduling. The measure is used to calculate both a relative score for the RBs for a user, and a global score on energy efficiency considering all users. The scheduler increases the number of scheduled RBs, if proven to be more energy efficient, when the system is underloaded.

[0009] The present invention provides a method of operating a mobile telecommunications system having a base station, a plurality of users and a plurality of spectral resource blocks, some of which are not allocated to users, the method comprising (a) for each user, assigning a score to each resource block based on the energy efficiency with which the user can use the resource block, and determining which of the plurality of resource blocks is favored, i.e. has a score indicating that it will be the most energy efficient for the user; and for each user; either (b) if the user's favored resource block is not allocated, and is not favored by any other user, allocating that resource block to that user or (c) in the event that the same resource block is favored by more than one user, allocating it to the user who will use it with the greatest energy efficiency.

[0010] Calculation of the energy efficiency in step (a) may comprise calculating the transmission power, the energy per transmitted bit, the total required energy for a transmission or a combination of more than one of these.

[0011] The method may involve repeating steps (b) and (c) until either (i) all of the resource blocks have been allocated, or (ii) all users' QoS constraints have been satisfied and no user's energy efficiency would be increased by a further resource block.

[0012] In order to avoid compromising the QoS (quality of service), resource blocks that cannot achieve a minimum signal-to-interference-to-noise ratio (SINR) may be removed from consideration in step (a).

[0013] To promote fairness, a penalty function of each user may be changed whenever the user is allocated a further resource block, the penalty function being used to modify the score and reduce the chance of that user being allocated further resource blocks. The penalty function may for example comprise a power of the number of resource blocks already allocated to a user or a constant raised to the power of that number.

[0014] The method may further include expanding a bandwidth footprint and reducing a modulation complexity of at least one user. In particular, from another aspect, the present invention provides a method of operating a mobile telecom-

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munications system having a base station, a plurality of users and a plurality of spectral resource blocks, some of which are not allocated to users, the method comprising (p) determining whether there are free resource blocks; (q) if so, recalculating the scores for the free resource blocks according to step (a); (r) determining which of the users would increase the overall system energy efficiency most if the user's bandwidth were expanded; (s) determining that user's additional favored resource blocks using the score recalculated in step (q) and (t) allocating the additional favored resource block(s) to the user and causing the user to enter an extended-bandwidth transmission mode. This may in particular involve expanding the user's total bandwidth by a factor that is a natural number and reducing the user's modulation complexity accordingly. Optionally, it may additionally involve manipulating other link parameters such as the coding scheme or coding rate.

[0015] The user entering extended-bandwidth transmission mode may be removed from consideration for a subsequent bandwidth expansion. Steps (p) to (t) may then be repeated until step (p) finds that there are no more free resource blocks.

[0016] The method of the invention may involve a power control routine which minimizes the signal strength allocated to each channel. This may be performed after step (c) and/or after step (t).

[0017] The invention also provides a base station adapted to perform the method set out above.

BRIEF DESCRIPTION OF THE DRAWINGS

[0018] The invention will now be described in more detail, by way of example only, with reference to the accompanying drawings, in which:

[0019] FIG. 1 is a flow chart showing the method of the invention;

[0020] FIG. 2a schematically shows a scenario for two users;

[0021] FIG. 2b plots the required transmission power of the users of FIG. 2a under frequency selective fading;

[0022] FIG. 3 schematically shows a simulation scenario;

[0023] FIGS. 4a, 4b and 4c are graphs of data rate results;

[0024] FIG. 5 is a graph showing relative energy consumption gain; and

[0025] FIG. 6 shows the LTE frame structure.

DETAILED DESCRIPTION OF PARTICULAR EMBODIMENTS

[0026] The invention employs a score-based scheduler. T. Bonald, "A Score-Based Opportunistic Scheduler for Fading Radio Channels," in *Proc. of the European Wireless Conference (EWC)*, Barcelona, Spain, Feb. 24-27 2004 has described a score-based scheduler that determines QoS or throughput. The scheduler of the invention, by contrast, aims at optimizing spectral efficiency, fairness and energy efficiency, whilst ensuring that the QoS is not compromised.

[0027] An overview of the operation of the proposed technique is presented in the form of a flowchart in FIG. 1. The allocation routine starts by using a score-based scheduler that relies on channel gains, interference characteristics and an energy metric to find the most energy-efficient resource blocks (RBs) to transmit on.

[0028] It is based on the following equation:

$$s_i^k(t) = 1 + \sum_{j=1, j \neq i}^W \Pi_{E_j^k(t) > E_i^k(t)} + f^k(n) \quad (1)$$

where $s_i^k(t)$ is the score for RB i at time t for user k , W is the total number of RBs available for allocation to the user at the time, $E_i(t)$ is the energy metric for RB i at time t and user k , and $f^k(n)$ is a penalty function for user k . Lower RB scores mean a RB is more likely to be allocated. The penalty function is used to further promote fairness in the system, as well as to provide convenient means to control the resource distribution.

[0029] The energy metric can be any measure that assesses the energy performance of a wireless transmission. For example, it can be the transmission power required, the energy per transmitted bit, or the total required energy to transmit. RBs that cannot achieve the required minimum signal-to-interference-and-noise ratio (SINR) are given a score of infinity and are hence not allocated. Conflicts are resolved by calculating the energy efficiency scores for all users, and allocating the conflicting RBs to the users who can use them most efficiently. The rest of the conflicting users are allocated their next best resource. Consider the example in FIG. 2, which illustrates how fairness is promoted within the scheduling algorithm. The y-axis in FIG. 2b plots the required transmit power to achieve a certain SINR at the particular user. One user (user 2) is severely disadvantaged by the combination of path gain and interference, as shown in FIG. 2a. The two users happen to have the same RB as their best one (which corresponds to the lowest score in (1)) denoted by 1. The system then allocates this resource to the user who can use it more efficiently of the two, R_{x_1} . The penalty of that user will be increased so that in a similar conflict situation the resource will be given to the other user in contention. In the example, the second user is then allocated his next best available resource, which might be either 2 or 3.

[0030] The penalty function can be tailored to specific requirements. For example, it can take n , the number of already allocated RBs to the user, as input, and be of the form n^2 or even 2^n . One can envision penalty functions that mimic the behavior of already popular schedulers such as proportional fair etc. The procedure is repeated until the QoS constraints within the base station (BS) are satisfied, or it is found that it is impossible to do so. At the end, a stable energy-efficient resource allocation is achieved.

[0031] The invention further involves trading bandwidth for energy efficiency. It has often been mooted that energy can be saved in wireless networks by trading bandwidth for spectral efficiency. However, to the best of our knowledge there is no concrete technique that describes how this finding is implemented in a real world system, or a detailed theoretical discussion of the expected gains.

[0032] The extended-bandwidth transmission mode of the invention is able to provide energy savings, since a channel's throughput is linearly proportional to the amount of bandwidth available, and only logarithmically proportional to the transmission power. The aforementioned is derived from the Shannon channel capacity equation:

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$$C = B \log_2 \left(1 + \frac{S}{N + I} \right) \quad (2)$$

where C is the channel capacity, B is the channel bandwidth, S is the total received signal power over the bandwidth, N is the total noise power, and I is the total interference power.

[0033] Thus, after running the score-based scheduler discussed above, the system checks if there are resources available that can be used to reduce the energy footprint of the current communication links. In case there are no free RBs, the allocation procedure is complete. However if there are resources available, the system proceeds to evaluate which users should be allowed to enter an extended-bandwidth transmission mode. The total bandwidth footprint of a user is expanded by a factor that is a natural number. Where the factor is a power of two, bandwidth expansion may be achieved by simply reducing the modulation alphabet. However when the coding rate (type of code used) is also varied, then the bandwidth expansion factor can be any natural number. Thus, the bandwidth expansion technique may involve adjusting link parameters other than modulation complexity, such as coding rate. This results in an energy saving if the channel conditions on the newly allocated RBs are comparable to the ones on the already used ones. The scheduling mechanism calculates if there will be such a saving. This is done using the energy metric employed in the score-based scheduler. The RBs to be additionally allocated are chosen based on their scores calculated using (1).

[0034] The user who is able to achieve the highest absolute energy reduction is allowed to enter the extended bandwidth transmission mode. That user is removed from the set of users considered for the next iteration of the algorithm. The process is repeated within the BS until there is no more bandwidth available, or no user can benefit from being allocated additional RBs. To achieve meaningful results, a power control routine is run concurrently with the allocation algorithm in the system.

[0035] To test the performance of the proposed scheduling algorithm, a simple 2-link simulation platform was developed. It is based on the LTE cellular mobile telephony system. It is used to compare three systems—one making use solely of the amended score-based scheduler, another making use of both the score-based scheduler and the bandwidth expanded transmission mode (BEM), and a third benchmark system that makes use of the widely-used proportional fair (PF) scheduling.

Simulation Set-Up and Scenario

[0036] The set up that is simulated can be seen in FIG. 3. It is a simple 2-link scenario that allows for the adjustment of three parameters—the two distances between receivers and transmitters, d_1 and d_2 , and the transmitter radius, R, which controls the inter-site distance. Communication is carried out in the downlink direction.

[0037] The channel model used is the LTE urban micro-cell (UMi) (see 3GPP, "Further Advancements for E-UTRA Physical Layer Aspects (Release 9)," 3GPP TR 36.814 V0.4.1 (2009-02), September 2009. Retrieved Jun. 2, 2009 from www.3gpp.org/ftp/Specs/) as defined in Table 1, where d is the distance between transmitter and receiver, f_c is the carrier frequency in MHz, h_{BS} is the elevation of the base station (BS)

antenna, h_{UT} is the elevation of the user terminal antenna, and d_{BP} is the propagation break point distance. In practice one of the three path loss equations is selected, based on d.

TABLE 1

Channel Model		
	Path Loss [dB]	St. dev [dB]
LOS	$L = 22 \log_{10}(d) + 28 + \log_{10}(f_c)$	$\sigma = 3$
	$L = 40 \log_{10}(d) + 7.8 - 18 \log_{10}(h_{BS} - 1) -$	$\sigma = 3$
	$18 \log_{10}(h_{UT} - 1) + 2 \log_{10}(f_c)$	
NLOS	$L = 26.7 \log_{10}(d) + 22.7 + 26 \log_{10}(f_c)$	$\sigma = 4$

[0038] The rest of the system parameters are taken as prescribed in the LTE Advanced documentation, and can be found in Table 2.

TABLE 2

System Parameters	
Parameter	Value
Total Bandwidth	18.75 MHz
Carrier Frequency	2 GHz
Resource Bandwidth	375 kHz
Number of Resource Blocks (RBs)	50
Subcarriers per RB	8
Noise Floor	-178.23 dBm
BS Maximum Power	46 dBm
User Speed	3 m/s
SINR targets, Γ_i	3.7 dB
Data rates	1, 2 bits/symbol
Resources per User, x	8
Inter site distance	200 m
User 1 distance	50 m
User 2 distance	50 m
Bandwidth expansion factor, α	2

[0039] Since the scheduler is the main focus of the simulation, the implementation pseudo-code is presented in Algorithm 1. Once the amended score-based scheduler achieves a stable allocation i.e. after a few time slots, the bandwidth expansion routine found in Algorithm 2 is run. Two system performance parameters are used for evaluation—data rate, and energy consumption gain. Energy consumption gain (ECG) is a comparison between two systems where E_1 is taken as the reference system: $ECG = E_1/E_2$. It is used to compare the performance of the two systems.

ALGORITHM 1 - AMENDED SCORE-BASED SCHEDULER

```

INITIALIZE the number of required RBs for each user
while Users require RBs do
    CALCULATE scores for all users based on the energy metric and
    score equation
    for i = 1 to number of RBs do
        FIND each user's best RB for the ones connected to this BS
        if User's best RB is not allocated AND is usable AND is not
        another user's best RB then
            ALLOCATE RB to user
        end if
        if There were conflicting RBs between users then
            RESOLVE conflicts by allocating RB to most efficient
            user, and allocate next best RBs to the remaining users
        end if
    end for
    if There are no available RBs for allocation OR no users require more

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-continued

Algorithm 1 - Amended score-based scheduler

```

RBs then
  EXIT while loop
end if
end while
RUN power control algorithm

```

Algorithm 2 - Bandwidth expansion routine

```

while There is available bandwidth do
  CALCULATE scores for all users based on the energy metric and
  score equation
  FIND how much the system can benefit in absolute energy terms
  from expanding each user's bandwidth
  FIND the user for each BS who can benefit the most while not
  hurting the overall network efficiency
  ALLOCATE the required RBs to the best users
end while
RUN power control algorithm

```

Results

[0040] The simulation platform was run with the aforementioned scenario and parameters. The results presented here are averaged over 1000 random channel realizations.

[0041] The data rate results are presented in FIGS. 4a, 4b and 4c. All systems behave very similarly. The PF system exhibits very slight service degradation for a small percentage of the users. The combination of fixed SINR target and number of RBs required per user result in the fixed/constant data rate achieved for all systems. Any deviation from that value is due to an incomplete allocation i.e. a lack of usable RBs or a failure to allocate such.

[0042] The cumulative distribution function of ECG is plotted in FIG. 5. The region to the right of ECG of 1 means that the evaluated system performs better than the benchmark (in this case, the score-based scheduling system). The performance advantage of the hereby proposed score-based scheduling system is immediately apparent. The PF system performs significantly poorer for about 98% of the time. At the 50th percentile, it performs approximately 1.8 times worse than the proposed system. The system with BEM transmission capabilities further improves on the performance of the score-based system.

[0043] The simulation results provide empirical evidence that the proposed system is able to enhance energy efficiency. This is done at no cost to the delivered QoS to the users. A reduction of almost 50% in expended energy is achieved as compared to the benchmark PF system.

Energy Metrics in Energy-Efficient Scheduling

[0044] It is clear that the energy metric that is used plays an important role in making scheduling decisions. In the above simulation results, the energy metric $E_{i,k}(t)$ denoted in (1) is calculated as the required RF energy for the data transmission. However, note that in general there are a number of ways to compute the Energy metric that may lead to different scheduler outcomes. There is a number of different forms of the energy metric $E_{i,k}(t)$ that can be used:

[0045] RF Energy for Data Transmission: In this case, the scheduler only considers the RF energy associated with the data that is being transmitted.

[0046] RF Energy for Data and Signaling Transmission: A second possible metric is the total RF energy consumption for delivering both the required control signaling and user data. As shown in FIG. 6, LTE control signaling generally includes reference signals for channel estimation, synchronization signals, broadcast channels, user specific resource assignments, etc., which can consume from 5-25% of total wireless resources in each radio frame. The control signaling also contributes a large amount of energy consumption, especially in the bandwidth expansion mode where user data consumes less RF energy. The use of this metric in conjunction with the blank subframe concept is described further in the next subsection.

[0047] Total Base Station Energy Consumption: A third option for the scheduler is to measure the total base station energy consumption to transmit the data under consideration. This requires a mathematical model that can convert the RF energy consumption and other parameters, such as the traffic load, into an equivalent energy consumption figure for the base station. This allows the scheduler to include the operational BS energy including for example power rectification, RF amplification, transceiver signal processing, base station cooling and so on.

[0048] Selecting an appropriate energy metric for scheduling depends on the network operator, however the computational complexity associated with the metric should be considered.

Blank Subframe Concept

[0049] The use of energy metrics such as the RF energy for signaling and data transmission option above allows the scheduler to be applied to wireless systems that can exploit the blank subframe concept described in R. Wang, J. Thompson, and H. Haas, "A Novel Time-Domain Sleep Mode Design for Energy-Efficient LTE," *International Symposium on Communications, Control and Signal Processing*, March 2010. With blank subframes, the system delivers all the user information within the active subframes while stopping the transmission of other subframes that contain no user data during a defined period of time. Energy savings can be obtained due to not transmitting control signaling in non-active subframes. Combining blank subframes into the energy-efficient scheduler of the present invention could further reduce the energy consumption.

[0050] Optimizing the number of blank subframes can easily be incorporated into our energy-efficient scheduling framework. The comparison of energy consumption in (1) for resource allocation determines how we select the best transmission option. The scheduler may thus consider different transmission modes which use different numbers of blank subframes. With the bandwidth expansion mode, this becomes even more important as the wider bandwidth may lead to an increased portion of control signaling. If this trade-off is to be optimized, the energy used for both the transmission of control and channel data for the subframes should be explicitly taken into account when making decisions to expand bandwidth or not within the scheduler to ensure the highest energy savings. Moreover, techniques such as transmission data aggregation could further improve the energy

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efficiency of a system that is able to employ blank subframes as well as extend bandwidth. In such a scenario, transmissions could be carried out only when it is necessary to satisfy the QoS, and hence maintain the best possible efficiency.

[0051] The invention is of particular interest when the wireless network is not fully loaded and when there are spare frequency resources available. For this scenario, the invention provides a novel scheduling algorithm which takes into account an energy efficiency metric in the scheduling process. In the past, the optimization criteria merely have been spectral efficiency and fairness. The scheduler of the invention addresses a third dimension, that is energy efficiency and the way this is leveraged is by exploiting the mechanism of expanding the bandwidth when it is available and at the same time using modulation schemes which require less power. The key advantage is that overall energy is reduced while QoS and throughput is retained. As mentioned above the scheduling mechanism of the invention can also work with other energy saving techniques, and even with multiple ones at the same time.

1. A method of operating a mobile telecommunications system having a base station, a plurality of users and a plurality of spectral resource blocks, some of which are not allocated to users, the method comprising (a) for each user, assigning a score to each resource block based on the energy efficiency with which the user can use the resource block, and determining which of the plurality of resource blocks is favored, i.e. has a score indicating that it will be the most energy efficient for the user; and for each user, either (b) if the user's favored resource block is not allocated, and is not favored by any other user, allocating that resource block to that user; or (c) in the event that the same resource block is favored by more than one user, allocating it to the user who will use it with the greatest energy efficiency.

2. A method according to claim 1, wherein calculation of the energy efficiency in step (a) comprises calculating the transmission power.

3. A method according to claim 1, wherein calculation of the energy efficiency in step (a) comprises calculating the energy per transmitted bit.

4. A method according to claim 1, wherein calculation of the energy efficiency in step (a) comprises calculating the total required energy for a transmission.

5. A method according to claim 1, including repeating steps (b) and (c) until either (i) all of the resource blocks have been allocated or (ii) all user quality-of-service constraints have been satisfied and no user's energy efficiency would be increased by a further resource block.

6. A method according to claim 1, wherein resource blocks that cannot achieve a minimum signal-to-interference-to-noise ratio (SINR) are removed from consideration in step (a).

7. A method according to claim 1, wherein a penalty function of each user is changed whenever the user is allocated a further resource block, the penalty function being used to modify the score and reduce the chance of that user being allocated further resource blocks.

8. A method according to claim 7, wherein the penalty function comprises a power of the number of resource blocks already allocated to the user.

9. A method according to claim 7, wherein the penalty function comprises a constant raised to the power of the number of resource blocks already allocated to the user.

10. A method according to claim 1, further comprising the steps of (p) determining whether there are free resource blocks; (q) if so, recalculating the scores for the free resource blocks according to step (a); (r) determining which of the users would increase the overall system energy efficiency most if the user's bandwidth were expanded; (s) determining that user's additional favored resource block(s) using the score recalculated in step (q); and (t) allocating the additional favored resource block(s) to the user and causing the user to enter an extended-bandwidth transmission mode.

11. A method of operating a mobile telecommunications system having a base station, a plurality of users and a plurality of spectral resource blocks, the method comprising (p) determining whether there are free resource blocks; (q) if so, assigning a score to each resource block based on the energy efficiency with which the user can use the resource block, and determining which of the plurality of resource blocks is favored, i.e. has a score indicating that it will be the most energy efficient for the user; (r) determining which of the users would increase the overall system energy efficiency most if the user's bandwidth were expanded; (s) determining that user's favored resource block(s) using the score calculated in step (q); and (t) allocating the additional favored resource block(s) to the user and causing the user to enter an extended-bandwidth transmission mode.

12. A method according to claim 11, wherein step (t) includes expanding the user's total bandwidth by a factor that is a natural number and reducing the user's modulation complexity accordingly.

13. A method according to claim 12, wherein step (t) additionally includes manipulating at least one other link parameter of the user.

14. A method according to claim 11, wherein the user entering extended-bandwidth transmission mode is removed from consideration for a subsequent bandwidth expansion.

15. A method according to claim 11, wherein steps (p) to (t) are repeated until step (p) finds that there are no more free resource blocks.

16. A method according to claim 1, including a power control routine which minimizes the signal strength allocated to each channel.

17. A method according to claim 16, wherein the power control routine is performed after step (c).

18. A method according to claim 11, including a power control routine which minimizes the signal strength allocated to each channel.

19. A method according to claim 18, wherein the power control routine is performed after step (t).

20. A method according to claim 1, wherein signaling data is not transmitted during at least one subframe in which user data is not transmitted.

21. A base station adapted to perform the method of claim 1.

* * * * *